GEOHAZARDS

GH0001 / **GEOHAZARDS / Seismogenic (Earthquakes)**

Earthquake

Definition

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the Earth (USGS, no date).

Reference

USGS, no date. Earthquake glossary. United States Geological Survey (USGS). https://earthquake.usgs.gov/learn/glossary/?term=earthquake Accessed 14 October 2020.

Annotations

Synonyms

Earth tremor.

Additional scientific description

Earthquake hazards are the physical phenomena that result from the occurrence of an earthquake. Primary earthquake hazards are those phenomena that occur most directly from an earthquake: ground shaking, landslides (and debris flow), liquefaction, surface rupture (and fissures), and subsidence/uplift. Secondary earthquake hazards are those that are caused by primary hazards, and include tsunami, seiche, flooding, fire and ground gases (PNSN, no date).

Metrics and numeric limits

Earthquake magnitudes are given using one of several broadly equivalent scales. The 'Moment magnitude' (Hanks and Kanamori, 1979) scaling is the preferred measure of an earthquake's size, as it quantifies the energy released by the earthquake and unlike other scales, does not saturate for large-magnitude events. Magnitude scales are a logarithmic scale; each increase of 1 magnitude unit (i.e., 4.3 to 5.3) represents an order of magnitude (factor of 10) increase in the amplitude of seismic measurements, and a factor of 32 increase in the energy release of an earthquake (USGS, no date a).

Earthquakes of magnitude 7.0 and above can be expected to cause widespread, intense ground shaking as well as other primary and secondary hazards; earthquakes of magnitudes 6.0 to 6.9 may cause local damage, while smaller earthquakes can cause damage to vulnerable structures at near-source distances. Note that damage may be more severe and widespread for an earthquake of a given magnitude and other characteristics in regions of fragile buildings, high-density populations or regions with local soil conditions that promote the amplification of ground shaking.

There are many different metrics for measuring the effects of earthquakes at a particular location. Qualitative intensity measures, like the Modified Mercalli intensity (MMI) scale (Wood and Neumann, 1931), and similar scales such as the Medvedev-Sponheuer-Kárník (MSK) scale or the European Macrointensity Scale (EMS-98) (Grünthal, 1998), describe the severity of an earthquake in terms of its effects on the Earth's surface, the infrastructure and the population (USGS, no date b). Modified Mercalli intensity values range from I (not felt) to XII (Total Damage), and the threshold for structural damage begins at VI, although this varies according to the fragility of buildings in a given region. For some earthquake reporting agencies, MMI XI and XII are no longer assigned and MMI X is available but has not been applied in recent times. Since 1931, it has become clear that many of the phenomena described by Wood and Neumann (1931) were less related to ground shaking, and more to other factors that would promote widespread destruction (Dewey et al., 1995).

Some of the other quantitative measures of ground shaking by seismic instruments include: the global map of earthquake hazard and risk produced by the Global Earthquake Model Foundation (GEM, 2018), the metric 'European Macroseismic Scale' for measuring the effects of earthquakes at a particular location (Grünthal, 1998), and ShakeMap®, developed by the U.S. Geological Survey (USGS, no date b).

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Earthquakes and associated (primary and secondary) hazards killed nearly 750,000 people between 1994 and 2013, more people than all other natural hazard disasters combined (CRED, 2015).

While technology does not yet exist for reducing earthquake hazards, the risk to buildings and infrastructure and human population can be mitigated by seismic retrofitting of existing buildings, improved compliance with seismic safety building guidelines, and avoidance of building on cliff faces, soft soils or next to an active fault.

The most common and effective measure for mitigating earthquake risk is by implementing building codes with provisions for earthquake safety. For example, the US Federal Emergency Management Agency (FEMA, 2020) hosts a useful website on Seismic Building Codes.

The Global Earthquake Model Foundation recently produced a global map of earthquake hazard and risk (GEM, 2018) and is releasing the underlying national and regional models. Many of GEM's hazard models have been developed by or in collaboration with national governments for seismic design regulations in building codes

Some success has also been achieved in the development of early warning systems, which detect earthquakes close to the source or fault rupture, and trigger warnings to more distant locations, providing seconds to minutes of advance warning (Gasparini et al., 2007). Examples include the warning system for Japan's bullet trains, and Mexico City's warning system for evacuating vulnerable buildings.

References

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USGS, no date b. ShakeMap scientific background. United States Geological Survey (USGS). https://earthquake.usgs.gov/data/shakemap/background.php Accessed 14 October 2020.

Wood, H.O. and F. Neumann, 1931. Modified Mercalli intensity scale of 1931. Bulletin of the Seismological Society of America, 21:277-283.

Coordinating agency or organisation

Global Earthquake Model Foundation (GEM).

GH0002 / **GEOHAZARDS / Seismogenic (Earthquakes)**

Ground Shaking (Earthquake)

Definition

Earthquake ground shaking is the movement of the Earth's surface produced by seismic waves that are generated when an earthquake occurs (adapted from USGS, no date).

Reference

USGS, no date. Earthquake glossary. United States Geological Survey (USGS). earthquake.usgs.gov/learn/glossary/?term=ground%20motion Accessed 14 October 2020.

Annotations

Synonyms

Seismicity, Shaking intensity, Ground motion, Ground vibration, Local ground response, Vibration.

Additional scientific description

Earthquake ground shaking is produced by waves that are generated by sudden slip on a fault that travel through the Earth and along its surface (USGS, no date a). All earthquakes, both natural and man-made, generate seismic waves. Seismic waves radiate outward from the earthquake origin, forming a circular wave front that causes shaking over an extended region (Stein and Wysession, 2003).

The strength and duration of the ground shaking at any given location depends on many factors, predominantly the magnitude of the earthquake, distance to earthquake origin, and local soil conditions. Thus, at each site, ground shaking from an earthquake is unique and can vary significantly from location to location (USGS, no date b).

Ground shaking is the predominant seismic hazard (secondary seismic hazards include liquefaction, surface rupture, landslides etc.), causing more than 90% of earthquake damage and losses (National Institute of Building Sciences Building Seismic Safety Council, 2010).

Earthquake ground shaking scales with the source earthquake's magnitude, as well as the distance from the earthquake to a particular location, the depth of the earthquake, and the properties of the rock and soil between the earthquake and a given observation site.

Earthquake magnitudes are given using one of several broadly equivalent scales, with the 'moment magnitude' scaling being the preferred measure of an earthquake's size, as it quantifies the energy released by the earthquake (USGS, no date c). The magnitude scale is logarithmic; each increase of 1 magnitude unit (i.e., 4.3 to 5.3) represents an order of magnitude (factor of 10) increase in the amplitude of seismic measurements, and a factor of 32 increase in the energy release of an earthquake (USGS, no date a). Earthquakes of Magnitude 7.0 and above tend to cause widespread, intense ground shaking; while earthquakes of Magnitudes 6.0 to 6.9 may cause local damage. Note that damage may be more severe and widespread for an earthquake of a given magnitude and other characteristics in regions of fragile buildings and high-density populations.

Metrics and numeric limits

Although there is no globally agreed metric available, there is a global earthquake risk model (GEM, 2018) and other initiatives from the Global Earthquake Model Foundation (GEM) including a Global Exposure Database for Multi-Hazard Risk Analysis. The Peak Ground Acceleration method for measuring ground shaking is the preferred approach (Pagani et al., 2018), but global use is limited by the distribution of instrumentation.

There are many different metrics for measuring ground shaking at a particular location:

Qualitative intensity measures, like the Modified Mercalli intensity (MMI) scale, and similar scales such as the Medvedev-Sponheuer-Kárník (MSK) scale or the European Macrointensity Scale (EMS-98) (Grünthal, 1998) describe the severity of an earthquake in terms of its effects on the Earth's surface and on people and structures (USGS, no date a). MMI values range from I (not felt) to XII (Total Damage), and the threshold for structural damage begins at VI, although this varies with the fragility of buildings in a given region. For some earthquake reporting agencies, MMI XI and XII are no longer assigned and MMI X is available but has not been applied in recent times. Since 1931, it has become clear that many of the phenomena described by Wood and Neumann (1931) were less related to ground shaking, and more to other factors that would promote widespread destruction (Dewey et al., 1995).

Quantitative measures are direct measures of ground shaking by seismic instruments. A widely used and preferred metric for the strength of ground shaking is Peak Ground Acceleration (PGA). PGA is calculated as the greatest increase in velocity recorded by a particular station during an earthquake (USGS, no date a), and typically given in units of g (Earth's gravitational acceleration on its surface; 9.81 m/s2). It is an appropriate measure because the physical force exerted by the ground motions against any object on the surface is proportional to the peak acceleration. For engineering purposes, additional metrics such as spectral acceleration, which measure the forces experienced by structures at specified frequencies to which the structures may be particularly vulnerable. Generally, PGA values of less than 0.1 g are not expected to cause much damage, while values of between 0.2 g and 0.8 g may cause moderate damage; anything above this is expected to be very damaging (USGS, no date b). It is important to note that the amount of damage caused by ground motions of any given intensity in an area are highly dependent on the strength of infrastructure in that area. The largest recorded ground motion to date was 4.3 g in the 2008 Iwate-Miyagi earthquake, Japan (Yamada et al., 2010).

Ground shaking can last from a few seconds in small earthquakes to several minutes in the largest earthquakes.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Earthquakes are part of the natural tectonic process and will always occur (Stein and Wysession, 2003). Earthquakes, and therefore earthquake ground shaking, cannot be prevented, but their impacts on life, property, and the economy can be managed (National Institute of Building Sciences Building Seismic Safety Council, 2010).

Seismic risk from ground shaking is best managed through accurate estimation of the likelihood of seismic ground shaking at damaging levels, implementation of and conformance to appropriate building codes, and governmental and popular awareness and preparation for earthquakes.

References

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Pagani, M., J. Garcia-Pelaez, R. Gee, K. Johnson, V. Poggi, R. Styron, G. Weatherill, M. Simionato, D. Viganò, L. Danciu and D. Monelli, 2018. Global Earthquake Model (GEM) Seismic Hazard Map (version 2018.1 - December 2018). www.globalquakemodel.org/hazard-technical-description

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Coordinating agency or organisation

Global Earthquake Model Foundation (GEM).

GH0003 / **GEOHAZARDS / Seismogenic (Earthquakes)**

Liquefaction (Earthquake Trigger)

Definition

Soil liquefaction occurs when soil is transformed from a solid to a liquid state as a result of increased pore pressure and reduced effective stress. It is typically caused by rapid loading of the soil during earthquake shaking (AGI, 2017).

Reference

AGI, 2017. Liquefaction [soil]. American Geosciences Institute (AGI). www.americangeosciences.org/word/liquefaction-soil Accessed 14 October 2002.

Annotations

Synonyms

Not identified.

Additional scientific description

For liquefaction to occur, the shear strength of the soil volume (e.g., the strength due to contact between individual soil grains) must be reduced to near-zero. In the case of earthquakes, strong shaking applies a cyclic load to the soil body. If the soil body compresses under this load, the pore-water pressure will increase, causing the grains to separate thus reducing soil strength (Kramer, 1996).

Soil compression increases the pore-water pressure, causing the water to move toward the Earth's surface where pressure is lower. Under typical loading (e.g., from temperature changes, increased groundwater), the water then drains, and contact between grains retain their strength. However, when loading cycles occur rapidly, such as during an earthquake, intermittent drainage is prohibited, and liquefaction may initiate (Kramer, 1996).

The following characteristics are common to deposits most susceptible to liquefaction (Kramer, 1996):

- Loose, sandy soils (but liquefaction has occasionally been observed in gravels and coarse silts)
- Rounded, well-sorted grains (e.g., uniform grain size); these compact most easily
- Recently deposited, especially of Holocene age (<11.7 ky), uncompacted soils including human-made deposits
- Soils that are saturated, below sea level, or within a few meters of groundwater.

Some of the most common landforms in which liquefaction occurs are marshlands, riverbanks, beaches, and floodplains. Post-earthquake field studies have shown that earthquake-triggered liquefaction often recurs at the same locations (Kramer, 1996). Earthquake-induced liquefaction can have varied effects on the surrounding built environment. Buildings, infrastructure, and utilities normally supported by the soil may sink, or undergo cracking or other structural damage; pile foundations may buckle or tilt; and lightweight, buried masses such as pipelines may become buoyant and float to the surface. Liquefaction can also cause rapid settling of sediments, flooding (including breaches of earthen embankments or other retaining structures), and lateral spreading of soils (Kramer, 1996).

In general, sites closer to an earthquake's epicentre are more likely to liquefy, while the distance at which sites are susceptible to liquefaction increases with moment magnitude (MW) and the duration (or number of cycles) of ground motion.

The smallest earthquake for which liquefaction records exist was MW ~ 5, with the most distant observed liquefaction reaching only ~2 km; by contrast, the most distant liquefaction for an earthquake of MW >7, may exceed 100 km (Ambraseys, 1988). During the 2011 MW 9.0 Tohoku earthquake, damage due to liquefaction occurred at least 250 km from the epicentre (Yamaguchi et al., 2012).

Liquefaction susceptibility can be assessed in advance of earthquakes (e.g., Lirer at al., 2019). Often, this is based on a simplified indication of a site's likelihood to liquefy. A common approach is the liquefaction potential index (LPI), which considers a factor of safety against liquefaction, the layers of earth that might liquefy, and the proximity of these layers to the ground surface (Iwasaki et al., 1984). While several methods are available for determining the factor of safety, they generally reflect the ability of the soil to resist the power of an earthquake. Soil resistance is either measured in situ or estimated based on the surficial deposits and hydrological conditions (Kramer, 1996; Witter et al., 2006). The comparison to earthquake power can be deterministic for the worst-case scenario earthquake (Orhan et al., 2013), or probabilistic for the range of possible earthquakes that could occur (Witter et al., 2006).

Metrics and numeric limits

Liquefaction susceptibility maps (also called liquefaction hazard maps) are currently not available on a global scale but are often provided by the geological agencies in a region. See USGS (no date) for an example of a liquefaction map for the San Francisco Bay Area.

Key relevant UN convention/multilateral treaty

Not relevant.

Examples of drivers, outcomes and risk management

In-situ testing of liquefaction resistance using standard penetration tests, cone penetration tests, shear wave velocity recordings, and dilatometer tests (Kramer, 1996); land microzonation via LPI or another assessment parameter that prohibits building on susceptible deposits (Lirer et al., 2019); and soil stabilisation via compaction methods or injection of grout, such as vibro stone columns and dynamic compaction (Shenthan et al., 2004).

References

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Coordinating agency or organisation

Global Earthquake Model Foundation.

GH0004 / **GEOHAZARD / Seismogenic (Earthquakes)**

Earthquake Surface Rupture, Fissures, and Tectonic Uplift/Subsidence

Definition

Earthquake surface ruptures and fissures are localised ground displacements that develop during and immediately after an earthquake, where the fault which hosted the earthquake intersects the Earth's surface. Surface ruptures represent the upward continuation of fault slip at depth, while fissures are smaller displacements, or more distributed deformation in and around the rupture area (adapted from USGS, no date and PNSN, no date).

Tectonic uplift and subsidence are the distributed vertical permanent ground deformations (warping) that result from displacement on a dipping (inclined) fault (Styron, 2019).

References

PNSN, no date. Surface rupture. Pacific Northwest Seismic Network (PNSN). pnsn.org/outreach/earthquakehazards/surface-rupture Accessed 24 November 2019.

Styron, R., 2019. Coseismic uplift and subsidence: An underappreciated seismic threat. Global Earthquake Model Foundation (GEM) Hazard Blog. blogs.openquake.org/hazard/2019/11/19/coseismic-uplift-subsidence Accessed 24 November 2019.

USGS, no date. Surface faulting. United States Geological Survey (USGS). earthquake.usgs.gov/learn/glossary/?term=surface%20faulting Accessed 24 November 2019.

Annotations

Synonyms

Fault scarp, Fault displacement, Fault offset, Ground deformation, Surface faulting, Coseismic subsidence.

Additional scientific description

Most earthquakes are caused by displacement (sliding) of the Earth's crust at a fault. The relative motion of the crust on either side of the fault results in persistent or permanent deformation of the Earth's surface, in addition to the ground shaking resulting from the sudden release of energy during the earthquake. Surface ruptures, fissures, and uplift and subsidence are all manifestations of this longer-term deformation, and although less dramatic, may all pose hazards during and after earthquakes (Styron, 2019).

Metrics and numeric limits

The size and spatial extent of surface ruptures, fissures and uplift/subsidence depend on the type, magnitude and depth of the earthquake as well as the distance from the earthquake.

Surface ruptures are expected in about half of continental Magnitude 6 earthquakes, with an expectation that increases to 100% for continental earthquakes at Magnitude 8 and greater (Biasi and Weldon, 2006). Displacements vary from a few centimetres for earthquakes at the low end of this range and near the edges of larger earthquakes, up to 15–20 m for the largest possible continental earthquakes, around Magnitude 8 (Biasi and Weldon, 2006). Fissures are generally much smaller and more spatially distributed than surface ruptures.

Tectonic uplift and subsidence are generally as large or larger than the displacement of the surface rupture; moderate to large earthquakes in the crust that do not rupture to the surface will still broadly warp the region. The magnitude of the displacement will decrease with increasing distance from the earthquake, but in the case of ruptures on inclined faults such as subduction zones (rather than vertical strike-slip faults) uplift or subsidence of at least 1 m may extend more than 200 km from the fault trace for the largest earthquakes (Styron, 2019).

Both of these effects will extend along the length of the earthquake fault, a distance of a few kilometres for Magnitude 6 earthquakes to more than 1000 km for Magnitude 9 earthquakes.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Earthquake surface ruptures, fissures, and tectonic uplift/subsidence are caused by earthquakes of sufficient magnitude and proximity to the Earth's surface to cause permanent ground deformation. Surface ruptures and fissures are generally limited to the area near the causative fault's intersection with the Earth's surface, while uplift and subsidence can occur over a much broader region (Styron, 2019).

Surface ruptures and fissures can cause damage to buildings, roads, and utility infrastructure (e.g., gas and water lines). In addition to the immediate, local risk posed by collapsing infrastructure, this damage may hamper rescue and rebuilding efforts by impeding transportation and utility delivery. In the worst cases, damage to lifelines may cause local flooding (e.g., water lines), environmental impacts (e.g., oil pipelines) and even highly destructive fires (gas lines) that may be more damaging than the initial earthquake. There is also potential for disruption due to flooding or re-routing of rivers if the river channel is sufficiently modified (Holbrook and Schumm, 1999).

While no technology exists for reducing these or other earthquake hazards, the risk to infrastructure posed by surface rupture and fissures can be partly mitigated by not building on known fault traces, seismic retrofitting of existing buildings, and engineering of pipelines with enough flexibility to absorb the displacement by bending and flexing, rather than breaking (e.g., USGS, 2003).

Tectonic uplift and subsidence are not generally destructive, with the exception of earthquakes on coastal faults. These events, particularly large subduction zone earthquakes, can cause persistent (decades-long) or permanent reconfigurations of a coastline. Uplift during an earthquake can lead to dramatic decreases in the depth and utility of harbours. Subsidence during a Magnitude 8–9 subduction zone earthquake can cause coastal communities, highways, and other infrastructure to sink below sea level, and the establishment of a new shoreline inland by several tens to hundreds of metres.

References

Biasi, G.P. and R.J. Weldon, 2006. Estimating surface rupture length and magnitude of paleoearthquakes from point measurements of rupture displacement. Bulletin of the Seismological Society of America, 96:1612-1623.

Holbrook, J. and S.A. Schumm, 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics, 305:287-306.

Styron, R., 2019. Coseismic uplift and subsidence: An underappreciated seismic threat. Global Earthquake Model Foundation (GEM) Hazard Blog. blogs.openquake.org/hazard/2019/11/19/coseismic-uplift-subsidence Accessed 24 November 2019.

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Coordinating agency or organisation

Global Earthquake Model Foundation (GEM).

Subsidence and Uplift, Including Shoreline Change (Earthquake Trigger)

Definition

Tectonic uplift and subsidence are the distributed vertical permanent ground deformations (warping) that result from earthquake displacements on a dipping (inclined) fault (Styron, 2019). This includes changes to the shoreline as a result of uplift and subsidence.

Reference

Styron, R., 2019. Coseismic uplift and subsidence: An underappreciated seismic threat. Global Earthquake Model Foundation (GEM) Hazard Blog. blogs.openquake.org/hazard/2019/11/19/coseismic-uplift-subsidence Accessed 24 November 2019.

Annotations

Synonyms

Coseismic uplift/subsidence.

Additional scientific description

Most earthquakes are caused by displacement (sliding) of the Earth's crust at a fault. The relative motion of the crust on either side of the fault results in persistent or permanent deformation of the Earth's surface, in addition to the ground shaking resulting from the sudden release of energy during the earthquake. Tectonic uplift and subsidence are manifestations of this longer-term deformation, and though less dramatic, they may all pose hazards during and after earthquakes (Styron, 2019).

Metrics and numeric limits

The size and spatial extent of tectonic uplift or subsidence depends on the type, magnitude and depth of the earthquake as well as the distance from the earthquake.

Tectonic uplift and subsidence are generally as large or larger than the displacement of the surface rupture; moderate to large earthquakes in the crust that do not rupture to the surface will still broadly warp the region. The magnitude of the displacement will decrease with increasing distance from the earthquake, but in the case of ruptures on inclined faults such as subduction zones (rather than vertical strike-slip faults) uplift or subsidence of at least 1 m may extend more than 200 km from the fault trace for the largest earthquakes (Styron, 2019).

These effects will extend along the length of the earthquake fault, a distance of a few kilometres for Magnitude 6 earthquakes to more than 1000 km for Magnitude 9 earthquakes.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Tectonic uplift and subsidence are caused by earthquakes of sufficient magnitude and proximity to the Earth's surface to cause permanent ground deformation. Tectonic uplift and subsidence can occur over a broad region around the causative fault (GEM, 2019).

Tectonic uplift and subsidence are not generally destructive, with the exception of earthquakes on coastal faults. These events, particularly large subduction zone earthquakes, can cause persistent (decades-long) or permanent reconfigurations of a coastline. Uplift during an earthquake can lead to dramatic decreases in the depth and utility of harbours. Subsidence during a Magnitude 8–9 subduction zone earthquake can cause coastal communities, highways, and other infrastructure to sink below sea level, and the establishment of a new shoreline inland by several tens to hundreds of metres (Plafker, 1965).

References

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Coordinating agency or organisation

Global Earthquake Model Foundation (GEM).

GH0006 / **GEOHAZARDS / Seismogenic (Earthquakes)**

Tsunami (Earthquake Trigger)

Definition

Tsunami is the Japanese term meaning wave ('nami') in a harbour ('tsu'). It is a series of travelling waves of extremely long length and period, usually generated by disturbances associated with earthquakes occurring below or near the ocean floor (IOC, 2019).

Reference

IOC, 2019. Tsunami Glossary, 2019. Intergovernmental Oceanographic Commission (IOC), Technical Series, 85. Fourth Edition. IOC/2008/TS/85 rev.4. https://unesdoc.unesco.org/ark:/48223/pf0000188226?posInSet=1&queryId=aeb846ae-edfb-4d66-a03a-385a5d5897f0

Annotations

Synonyms

Not found.

Additional scientific description

A tsunami may also be referred to as a 'seismic sea wave' and, incorrectly, a 'tidal wave'. Volcanic eruptions, submarine landslides, and coastal rock falls can also generate tsunamis, as can a large meteorite impacting the ocean. These waves may reach enormous dimensions and travel across entire ocean basins with little loss of energy. They proceed as ordinary gravity waves with a typical period of between 10 and 60 minutes. Tsunamis steepen and increase in height on approaching shallow water, inundating low-lying areas, and where local submarine topography causes the waves to steepen, they may break and cause great damage (IOC, 2019).

Tsunami-like phenomena generated by meteorological or atmospheric disturbances are known as meteotsunami (UNESCO and IOC, 2019).

The Intergovernmental Oceanographic Commission (IOC) uses the following terms to assess the scale and impact of a tsunami (IOC, 2019):

Travel time: Time required for the first tsunami wave to propagate from its source to a given point on a coastline.

Arrival time: Time of the first maximum of the tsunami waves.

Inundation or Inundation-distance: The horizontal distance inland that a tsunami penetrates, generally measured perpendicularly to the shoreline.

Inundation (maximum): Maximum horizontal penetration of the tsunami from the shoreline. A maximum inundation is measured for each different coast or harbour affected by the tsunami.

Inundation area: Area flooded with water by the tsunami.

Inundation height: Elevation reached by seawater measured relative to a stated datum such as mean sea level or the sea level at the time of tsunami arrival, at a specified inundation distance. Inundation height is the sum of the flow depth and the local topographic height. Sometimes referred to as tsunami height.

Inundation line: Inland limit of wetting measured horizontally from the mean sea level line. The line between living and dead vegetation is sometimes used as a reference. In tsunami science, the landward limit of tsunami run-up.

Leading wave: First arriving wave of a tsunami. In some cases, the leading wave produces an initial depression or drop in sea level, and in other cases, an elevation or rise in sea level. When a drop in sea level occurs, sea level recession is observed.

Mean height: Average height of a tsunami measured from the trough to the crest after removing the tidal variation.

Run-up

- Difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami. In practical terms, run up is only measured where there is clear evidence of the inundation limit on the shore.
- Elevation reached by seawater measured relative to some stated datum such as mean sea level, mean low water, sea level at the time of the tsunami event, etc., and measured ideally at a point that is a local maximum of the horizontal inundation. Where the elevation is not measured at the maximum of horizontal inundation, this is often referred to as the inundation height.

Tsunami amplitude: Usually measured on a sea level record, it is (1) the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level at the time, (2) half the difference between an adjacent peak and trough, corrected for the change of tide between that peak and trough. It is intended to represent the true amplitude of the tsunami wave at some point in the ocean. However, it is often an amplitude modified in some way by the tide gauge response.

Tsunami period: Amount of time that a tsunami wave takes to complete a cycle, or one wavelength. Tsunami periods typically range from 5 to 60 minutes. Tsunami period is often measured as the difference between the arrival time of the highest peak and the next one measured on a water level record.

Tsunami wavelength: The horizontal distance between similar points on two successive waves measured perpendicular to the crest. The wavelength and the tsunami period give information on the tsunami source. For tsunamis generated by earthquakes, the typical wavelength ranges from 20 to 300 km. For tsunamis generated by landslides, the wavelength is much shorter, ranging from hundreds of metres to tens of kilometres.

For more terms see IOC (2019).

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Not available.

Examples of drivers, outcomes and risk management

Tsunamis are created by an underwater disturbance such as an earthquake, landslide, volcanic eruption, and meteorite or generated by meteorological or atmospheric disturbances.

Primary hazards/damage. Damage and destruction from tsunamis is the direct result of three factors: inundation, wave impact on structures, and erosion. Deaths occur by drowning and physical impact or other trauma when people are caught in the turbulent, debris-laden tsunami waves. Strong tsunami-induced currents have led to the erosion of foundations and the collapse of bridges and seawalls. Floatation and drag forces have moved houses and overturned railroad cars (IOC, 2019:6).

Tsunami associated wave forces have demolished frame buildings and other structures. Considerable damage is also caused by floating debris, including boats, cars, and trees that become dangerous projectiles that may crash into buildings, piers, and other vehicles. Ships and port facilities have been damaged by surge action caused by even weak tsunamis. Fires resulting from oil spills or combustion from damaged ships in port, or from ruptured coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami (IOC, 2019:6).

Secondary hazards/damage can result from sewage and chemical pollution following the destruction. Damage of intake, discharge, and storage facilities can also present dangers. Of increasing concern is the potential effect of tsunami drawdown, when receding waters uncover cooling water intakes associated with nuclear power plants (IOC, 2019:7).

Risk management for tsunamis includes guidelines on tsunami risk assessment/management. Examples include IOC (2015) and UNDRR (2017).

Regional Coordination and Centres: The IOC is coordinating the implementation of a global tsunami warning system, building upon its experiences in the Pacific to establish regional warning systems for the Indian Ocean (IOTWMS); Caribbean Sea (ICG-CARIBE-EWS); and the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS). The regional systems coordinate international tsunami warning and mitigation activities, including the issuance of timely and understandable tsunami bulletins to IOC Member States.

The Intergovernmental Coordination Group for Tsunamis addresses tsunami risk globally through the following groups:

ICG-PTWS Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System, formerly ICG/ITSU, was renamed by Resolution EC-XXXIX.8 of the IOC Executive Council in 2006 as proposed by the International Coordination Group for the Tsunami Warning System in the Pacific at its 20th Session in 2005 (Recommendation ITSU-XX.1). There are presently 46 Member States in the ICG-PTWS. ICG/ITSU, the International Coordination Group for the Tsunami Warning System in the Pacific was established by Resolution IV-6 of the 4th Session of the IOC Assembly in 1965. The Pacific Tsunami Warning Center (PTWC) serves as the Tsunami Service Provider (TSP) for the Pacific Ocean. Other TSPs for specific regions of the Pacific Ocean are the North West Pacific Tsunami Advisory Center (NWPTAC) and the South China Sea Tsunami Advisory Center (SCSTAC). The ICG-PTWS presently comprises over 40 Member States and oversees warning system operations and facilitates coordination and cooperation in all international tsunami mitigation activities.

ICG-IOTWMS The Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG-IOTWMS) was formed in response to the tragic tsunami on December 26th 2004, in which over 230,000 lives were lost around the Indian Ocean region. The ICG-IOTWMS comprises 28 Member States. There are three TSPs in the Indian Ocean, hosted by the governments of Australia, Indian and Indonesia.

ICG-NEAMTWS The Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS) was formed in response to the tragic tsunami on 26 December 2004, in which over 230,000 lives were lost around the Indian Ocean region (Indian Ocean Tsunami Information Centre, no date). The ICG-NEAMTWS consists of Member States bordering the North-eastern Atlantic and those bordering and within the Mediterranean and connected seas. There are currently five accredited Tsunami Service Providers (France, Greece, Italy, Portugal, Turkey) in the NEAM region providing tsunami services and alerts to subscribing Member States.

ICG-CARIBE-EWS The Intergovernmental Coordination Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG-CARIBE-EWS) was established in 2005 and currently comprises 32 Member States and 16 Territories in the Caribbean.

Tsunami Service Providers (TSPs) are centres that monitor seismic and sea level activity and issue timely tsunami threat information within an ICG framework to National Tsunami Warning Centres (NTWCs) / Tsunami Warning Focal Points (TWFPs) and other TSPs operating within an ocean basin. The NTWCs / TWFPs may use these products to develop and issue tsunami warnings for their countries. TSPs may also issue public messages for an ocean basin and act as NTWCs providing tsunami warnings for their own countries. Currently there are nine operational TSPs.

National Tsunami Warning Centres (NTWCs) are a centre officially designated by the government to monitor and issue tsunami warnings and other related statements within their country according to established national Standard Operating Procedures.

World Tsunami Awareness Day, 5 November every year: The United Nations, through UN Resolution 70/203 adopted on 22 December 2015, has designated 5 November as World Tsunami Awareness Day (UNDRR, 2020). The day aligns with the International Day for Disaster Reduction (13 October) and the seven targets of the Sendai Framework for Disaster Risk Reduction 2015–2030 (ITIC, 2020). The IOC is a key international partner of the UNDRR on World Tsunami Awareness Day.

Tsunami Ready is a voluntary community recognition programme that promotes tsunami hazard preparedness as an active collaboration among federal, state/territorial and local emergency management agencies, community leaders and the public. The main goal of the programme is to improve public safety before, during and after tsunami emergencies. It aims to do this by establishing guidelines for a standard level of capability to mitigate, prepare for and respond to tsunamis, and working with communities to help them meet the guidelines and ultimately become recognised as ‘tsunami ready’ by the National Weather Service. It was first implemented in the United States .To date, there are 26 IOC-UNESCO Tsunami Ready recognised communities in 18 countries and territories, excluding those implemented in the United States.

Community engagement with evacuation zones and the ‘blue lines’ project In New Zealand, the Wellington Region Emergency Management Office has developed the Blue Line Project in collaboration with communities in Wellington’s southern coastal suburbs. In this project, the local community helps to plan evacuation routes and safe locations based on indicative evacuation zone mapping, and blue lines are painted on the road surface at the maximum estimated tsunami inundation extent. Accompanying evacuation signage is installed. Community members are engaged early in the project, publicising the work and helping to develop blue line locations, evacuation zone maps and information boards. The communities participating in the Blue Line Project can be considered to have a higher degree of public education regarding tsunami evacuation than other communities (Fraser et al., 2016). Other communities around the world have used similar community engagement strategies.

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Coordinating agency or organisation

United Nations Educational, Scientific and Cultural Organization (UNESCO), Intergovernmental Oceanographic Commission (IOC-UNESCO) and the British Geological Survey.

Landslide or Debris Flow (Earthquake Trigger)

Definition

Landslide is the downslope movement of soil, rock and organic materials under the effects of gravity, which occurs when the gravitational driving forces exceed the frictional resistance of the material resisting on the slope. Landslides could be terrestrial or submarine (Varnes, 1978).

Reference

Varnes, D.J., 1978. Slope movement types and processes. In: Schuster, R.L. and R.J. Krizek (eds), Landslides, Analysis and Control. Special report 176: Transportation research board, National Academy of Sciences, Washington, DC. pp. 11-33.

Annotations

Synonyms

Mass Movement, Mass wasting, Slip.

Additional scientific description

A landslide is the movement of a mass of rock, debris, or earth down a slope; a type of 'mass wasting', which denotes any down-slope movement of soil and rock under the direct influence of gravity. The term 'landslide' encompasses five modes of slope movement: falls, topples, slides, spreads, and flows. These are subdivided according to the type of geologic material (bedrock, debris, or earth). Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope (Varnes, 1978).

Earthquake triggered landslides typically affect steep slopes and slopes underlain by sediments that are prone to liquefaction. Rock falls are the most abundant landslides in seismic events and occur in virtually all types of rocks on slopes steeper than 40° (Keefer, 1984). The behaviour of material on hillsides is highly dependent on the amplitudes of seismic waves that reach them, and this will vary with the epicentre distance and depth, as well as the magnitude (M) of an earthquake. Keefer (1984) from a study of historic earthquakes showed that the maximum area likely to be affected by landslides in a seismic event ranges from 0 km2 at M=4 to 500,000 km2 at M=9.2. Materials most susceptible to earthquake-induced landslide were found to include weakly cemented rocks, more indurated rocks with pervasive discontinuities, residual and colluvial sand, volcanic soils with sensitive clays (e.g., Iburi–Tobu earthquake, Hokkaido; Kameda et al., 2019), loess, alluvium and deltaic deposits. First-time slides were more common than landslide reactivation. Rock falls, rockslides, soil falls and disrupted soil slides were initiated by weak shaking; coherent deeper-seated landslides required stronger shaking; lateral spreads and flows required even stronger shaking, and rock and soil avalanches required the strongest shaking (Keefer, 1984).

Within a given region, it is possible to discriminate, earthquake-triggered landslides from landslides initiated by other triggering processes. For example, Lee (2012) reported that earthquake-induced landslides in Taiwan are mostly located on steeper, longer slopes and at a higher position of the slope when compared to storm-induced shallow landslides, suggesting that topographic amplification plays an important role in earthquake-induced landslides. In hard rock terrains, earthquakes trigger a higher proportion of rock fall landslides. Zhang et al. (2014) compared earthquake-triggered landslides with rainfall-triggered landslides in the Wenchuan area of China and found that the earthquake landslides were steeper, larger landslides dominated in areas underlain by harder rocks compared with areas underlain by alluvium. In contrast, the rainfall-induced landslides were characterised by a greater volume of channelled deposits and were of a higher density but smaller area and were characterised by debris slides and debris flows. In areas that are underlain by weak rocks that are saturated, strong earthquake-induced ground shaking will result in more landslides than normal (Fan et al., 2019).

Earthquake shaking and other factors can also induce landslides underwater. These are called submarine landslides. Submarine landslides sometimes cause tsunamis that damage coastal areas (Hungr et al., 2014).

Metrics and numeric limits

Landslide movement is likely to range from moderate in velocity (1.5 metres per day) to extremely rapid. With increased velocity, the landslide mass of translational failures may disintegrate and develop into a debris flow (Varnes, 1978).

Key relevant UN convention / multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Landslides can be extremely destructive, especially when failure is large, sudden and (or) the velocity is rapid.

Rapid soil flows, rock avalanches, and rock falls together caused more than 90% of the reported landslide deaths in the 40 historical earthquakes reported on by Keefer (1984). Rock avalanches and rapid soil flows, the two leading causes of death, are relatively uncommon, high velocity landslides that occur on slopes of a few degrees. Most deaths caused by these landslides were due to burial of cities or villages located on gently sloping ground several kilometres from the sites of landslide initiation. All but one death caused by soil slumps, block slides, or lateral spreads were due to disruption of foundations and subsequent collapse of buildings, most likely related to liquefaction. Aftershocks can be a significant trigger for further earthquake-induced landslides as reported by Liang and Zhou (2016) for the Gorkha earthquake, Nepal in 2015.

Earthquake triggered landslide impacts can cascade to dam rivers and impound lakes, which can collapse days to centuries later. They can cause extensive mountain valley flooding and leave a geomorphology that may be prone to remobilisation during heavy rainfall, potentially evolving as debris flows. Cracks and fractures can form and widen on mountain crests and flanks, conditioning the landscape for an increased frequency of landslides that lasts for decades. Increased debris load delivery to rivers can cause bank erosion and floodplain accretion as well as stream channel switching that affect flooding frequency, settlements, ecosystems, and infrastructure (Fan et al., 2019).

Instrumental monitoring to detect movement and the rate of movement can be implemented, for example, extensometers, global positioning system (GPS), seismometers, aerial photography, satellite images, LiDaR (Highland and Bobrowsky, 2008) with varying degrees of success.

While the physical damage of landslides is well documented, health impacts are complex. The risk of an increase in infectious diseases is of concern during the response and recovery phase after any major disaster. Displacement of people due to the destruction of their homes and other infrastructure can place them in unfamiliar surroundings which, if they conflict with traditional beliefs and practices with regard to water supply and hygiene, can result in unsafe behaviours. The medium- to long-term effects of changes to the environment caused by landslides, such as deforestation, and changes to river courses, can increase the risk of vector-borne diseases, and as a result, the health impacts can extend long after the initial disaster is over. Disruption of soil can also increase exposure to infectious organisms (Kennedy et al., 2015). The psychosocial and mental health impacts on survivors and rescue personnel from landslides are increasingly recorded. The prevalence of psychiatric disorders and wider support needed to reduce misuse of substances has been identified (Kennedy et al., 2015; Dell'Aringa et al., 2018). Landslides commonly occur in poor countries with steep terrain, such as the southern edge of the Himalayan arc. Increasingly, the science of landslide physics is allowing the nature of these hazards to be understood, which is leading to better techniques through which they can be managed and mitigated.

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Coordinating agency or organisation

British Geological Survey.

GH0008 / **GEOHAZARDS / Seismogenic (Earthquakes)**

Ground Gases (Seismogenic)

Definition

Ground gases generated in the ground from magma (molten or semi-molten natural material derived from the melting of land or oceanic crust) include carbon dioxide, sulphur dioxide, hydrogen sulphide and hydrogen halides (adapted from IVHHN, 2020 and USGS, no date).

References

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Annotations

Synonyms

Soil gases, Radon, Volcanic gases, Magmatic gases, Landfill gas, Gas-contaminated land.

Additional scientific description

Volcanogenic gases escape from magma as a consequence of the pressure relief that occurs as the magma rises to the surface. These gases are also released via geothermal systems and fault systems activated by earthquakes. King et al. (2006) found elevated concentrations of soil gases such as carbon dioxide, helium, hydrogen, mercury vapour and radon in fault zones associated with earthquakes. These gases are released in combination with water vapour and particulate matter during volcanogenic events, or via fumaroles, and hydrothermal systems, as well as faults activated by earthquake events. It has been suggested that radon monitoring might be used for earthquake early warning systems.

Earthquakes can also trigger the release of soil gases derived from other sources, such as the chemical or biological processes that generate ground gases, including the breakdown of uranium-bearing minerals releasing radon from granite or by oxidation and/or biogenic reduction (releasing hydrogen sulphide) as well as the release of anthropogenic stores of gas. For example, rupture of tanks and pipes (WHO, 2018), as well as landfill gas, a product of the largely biogenic decomposition of anthropogenic waste. Its composition reflects that of the waste, but is dominated by methane and carbon dioxide, becoming more carbon dioxide rich as the waste ages, and with a small amount of non-methane organic compounds. Methane is a potent greenhouse gas (US EPA, no date a).

Ground gases from material decay (natural or anthropogenic) typically include radon, methane, carbon dioxide, and hydrogen sulphide, but may also include the breakdown products of other compounds, such as nitrogen, alcohols, alkanes, cycloalkanes and alkenes, aromatic hydrocarbons (monocyclic or polycyclic); esters and ethers, as well as halogenated compounds and organosulphur (US EPA, no date b; USGS, no date).

Ground gases are a hazard owing to the risk to human health and/or their flammability. As an example, the UK limits for several gases are summarised below from sources other than earthquake triggered gases:

Methane is a colourless, odourless flammable gas. When the concentration of methane in air (oxygen 20.9% by volume, % v/v) is between the limits of 5% v/v and 15% v/v, an explosive mixture is formed. The Lower Explosive Limit (LEL) of methane is 5% v/v, which is equivalent to 100% LEL. The 15% v/v limit is known as the Upper Explosive Limit (UEL), but concentrations above this level cannot be assumed to represent safe concentrations, owing to the potential for dilution to the UEL (PHE, 2015).

Carbon dioxide is a colourless, odourless gas, which, although non-flammable, is both a toxic gas and an asphyxiant. As carbon dioxide is denser than air, it will collect in low points and depressions, which can be an extreme hazard during foundation construction and earth movements on development sites. the Long-Term Exposure Limit (LTEL, 8-hour period) and the Short Term Exposure Limit (STEL, 15-minute period), are 0.5% v/v and 1.5% v/v carbon dioxide, respectively (HSE, no date).

Radon is a colourless, odourless radioactive gas derived from the radioactive decay of radium, itself from radioactive decay of uranium. The UK target level for homes is 100 Bq/m3 (PHE, no date).

Levels of hydrogen sulphide of 100 ppm and higher are considered immediately dangerous to life and health (WorkSafe BC, no date).

Radon species, concentration and flux emitted in soil gas in active fault zones near Beijing have been reported by Chen et al. (2018), with a maximum flux of 334.56 mBq/m2/s being observed in the Fengnan district located at the epicentre of the 28 July 1976 earthquake. Chen et al. (2018) reported that these concentrations warrant mitigation measures and advised that fault zones in earthquake regions should be monitored as part of the pre-development land planning procedure.

Another source of ground gas with a potential for release by earthquake is methane hydrates associated with continental margins (Geology.com, 2005-2020).

Metrics and numeric limits

No globally agreed limits for ground gases (earthquake trigger).

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Ground gases are a hazard in terms of risk to human health, flammability and climate change (greenhouse gases). For these reasons, where possible, ground gas is monitored and controlled. Where buildings may come into contact with ground gases, specialist construction techniques are deployed to protect human health (e.g., Claire, 2021).

In the case of earthquake-triggered gases, consideration should also be given to the associated particulate matter. Landfill gas management has been a focal point for national-scale reductions in carbon dioxide emissions. For example, in 2018 waste management-related carbon dioxide formed 4.6% of UK carbon dioxide emissions (BEIS, 2020).

Ground gases occur in mining environments, for example, in the mining of coal (carbon dioxide and methane), potash (methane and nitrogen) and shale gas (BGS, no date). In the UK, control measures in these environments are guided by the Health and Safety Executive.

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Coordinating agency or organisation

Global Earthquake Model Foundation.

GH0009 / **GEOHAZARD / Volcanogenic (volcanoes and geothermal)**

Lava Flows (Lava Domes)

Definition

A lava flow or lava dome is a body of lava that forms during an eruption, or main eruptive episode. Lava flows are outpourings of fluid, relatively low-viscosity molten rock, whereas a lava dome is a pile of relatively viscous lava that cannot flow far from the vent (Calder et al., 2015; Kilburn, 2015).

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Annotations

Synonyms

Lava effusions, Lavas.

Additional scientific description

A lava flow may comprise smaller bodies of lava known as 'lava flow units', or 'lava flow lobes'; a lava flow comprising multiple lava flow units is known as a 'lava flow field'. Pillow lavas are lava flows formed under water. Lava domes may be described as a type, such as Peléan domes. Lava coulées are a hybrid between lava domes and flows, they are short, thick, viscous lava flows that typically form on a slope.

Most volcanoes erupt lava flows and/or domes during their lifetimes (Kilburn, 2015). Effusions of lava commonly continue from days to months, but occasionally for decades. Lava flows damage and destroy land and property but usually (not always) advance slowly enough for populations to escape. Understanding where future lava may be erupted from (the vent or vents), how far a lava flow may advance, the velocity of the flow front and the area that may be covered are critical for hazard assessments (Kilburn, 2015). Viscous lava flows and lava domes can generally be avoided but they may collapse to generate very hazardous pyroclastic density currents (Calder et al., 2015; Carr et al., 2019). The main factors controlling how a lava flow or dome develops are the lava's rheological properties, effusion (or extrusion) rate and underlying topography.

The rheological properties of lava are influenced by chemical composition. Fluid and mobile lava flows tend to be low in silica (e.g., mafic compositions such as basalt); lava with moderate silica content is more viscous and tends to form short blocky lava flows or lava domes (e.g., intermediate compositions such as andesite); the most silica-rich lava is most likely to form a lava dome (e.g., felsic compositions such as rhyolite). The Cordón Caulle eruption in 2011–2012, shows that rhyolitic and basaltic compound lava flows may have much in common in terms of physical processes, despite very different rheologies (Tuffen et al., 2013).

Parts of lava flows and lava domes can remain molten after an eruption has ended (e.g., Calder et al., 2015; Pederson et al., 2017) and this may lengthen the timescale of hazardous lava flow advance or potential for lava dome collapse.

Lava flow characteristics: Surface morphology of subaerial basaltic lava flows may be described as pāhoehoe (Hawaiian meaning 'smooth, unbroken') or aʻā (Hawaiian meaning 'stony, rough lava'), whereas intermediate or silica-rich lava is more likely to have a blocky surface morphology (Harris et al., 2017). Basaltic pāhoehoe flows commonly have the highest eruption temperatures of 1100 to 1200°C, whereas rhyolitic lavas are typically 650–750°C (Kilburn, 2015). The unique 'natrocarbonatite' lava flows at Ol Doinyo Lengai volcano in Tanzania are dominated by carbonates rather than silicates and form very fluid, relatively low temperature lavas (500–600°C) (Pinkerton et al., 1995).

At the start of an eruption, basaltic lavas may advance at several kilometres per hour, but slow to walking pace or less within a few hours (Kilburn, 2015). On steep slopes some lavas may reach higher velocities of tens of kilometres per hour. Exceptionally, in 1977, lava flowed down the slopes of Nyiragongo with a maximum velocity of up to 100 km/h (Balagizi et al., 2018). Viscous lavas may typically advance at rates of 0.1 km/day or less.

Typically, basaltic lava flows may reach lengths of 1–10 km, but occasionally more than 30 km (e.g., the Laki eruption in Iceland between 1783 and 1785; Thordarsson and Self, 1993) and some pāhoehoe flows have reached 50 km (Kilburn, 2015). Basaltic lava flows may be 3–20 m thick and typical volumes of historical lava flows on land are between 0.01 and 0.1 km3 (flow fields can exceptionally exceed 10 km3). Intermediate and silicic lavas are usually shorter in length, typically up to 5 km but some are up to 15 km. They may be 20–300 m thick and volumes are typically 0.01 and 0.1 km3 but can be up to 10–20 km3 (Kilburn, 2015).

Models: The simplest empirical models are volcano-specific and link effusion rate to runout length but more complex models account for cooling-induced changes in rheology as a lava flows over topography (e.g., Harris et al., 2013). New methodologies are constantly developing (e.g., Gallant et al., 2018) and generally have a two-step process: statistical analysis to establish known vent distributions and identify most likely future vent sites, followed by an estimation of the areas of inundation by lavas flowing from those vents (e.g., Connor et al., 2012). Outputs are highly sensitive to topography, as well as estimated volume of lava and flow dynamics (e.g., Dietterich et al., 2017). High resolution Digital Elevation Models are necessary (e.g., Turner et al., 2017) but in urban and man-made environments Digital Surface Models may be more appropriate (e.g., Tsang et al., 2020).

Probabilistic hazard assessments for lava flows can anticipate inundation so are useful for long-term planning (e.g., hazard maps) and short-term forecasting (e.g., Vicari et al., 2011). However, more study is required at many volcanoes that lack important metrics such as recurrence interval, or volume of previous lava flows (e.g., Wantim et al., 2018).

Lava flow and dome collapses: Viscous lava flows and domes may exhibit various collapse styles from persistent rock falls to partial or total collapse of a lava dome. Lava flow or dome collapse may generate potentially deadly pyroclastic density currents and associated hazards such as tephra and gas emissions (Calder et al., 2015; Harnett et al., 2019). Lava dome collapse hazard assessments are rarely in place but are needed (Harnett et al., 2019).

Metrics and numeric limits

Not identified.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Primary hazards. Lava flows may cause damage to buildings, infrastructure, communications, agriculture and environment by inundation, burial, transport, fire and explosion (e.g., Jenkins et al., 2017). Damage may not be complete but partial burial or inundation by lava generally makes buildings, infrastructure and land unusable (Jenkins et al., 2017). Buried infrastructure may also be destroyed due to thermal impacts (Tsang et al., 2020). Injuries may occur if individuals walk on a lava carapace with molten lava below. Health impacts may include burns, gas and aerosol inhalation. Viscous lava flows and domes in particular may be associated with episodes of explosive volcanic activity and additional primary volcanic hazards such as pyroclastic density currents, tephra and volcanic gases which in combination worsen the overall impact (Wantim et al., 2018).

Secondary hazards. Escape routes may be cut off, or the lavas may trigger explosions on meeting snow, ice and water, or flammable fluids. For example, in Goma in 2002, around 300,000 people self-evacuated and there were roughly 140 deaths, most caused by explosions at a petrol station that had been surrounded by lava (Balagizi et al., 2018). Lava flows may ignite forest or urban fires (e.g., Wantim et al., 2018). Volcanic gases and aerosols (air pollution) need to be considered, possibly over large areas (Barsotti et al., 2020). Evacuation to emergency accommodation may lead to permanent displacement, which if combined with loss of livelihoods and homes, may cause longer term mental and physical health impacts, and the long-term cascading effects can be more severe than immediate impacts (Wantim et al., 2018).

Between 1500 AD and 2017 there were 25 documented fatal incidents and 659 fatalities caused directly by lava flows, with fatalities occurring between 1 and 29 km of the volcanic source (median distance 11 km) (Brown et al., 2017). Fatalities and casualties occur when eruptions begin from vents close to towns and/or lavas are very fluid, on steep slopes and fast moving. For example, the 1977 eruption of Nyiragongo generated lava flows that killed about 70 people (Balagizi et al., 2018).

Viscous lava flows and lava domes do not directly cause fatalities and injuries, but their collapse may generate pyroclastic density currents which cause more fatalities than any other volcanic hazard (e.g., Calder et al., 2015; Brown et al., 2017).

If a volcanic area is well-monitored, the movement of magma in the subsurface may be detected days, weeks or even years before an eruption (e.g., Pederson et al., 2017; Pallister et al., 2019) enabling planning, preparation and emergency actions such as evacuation. Effective monitoring of the emplacement of lava flows and domes over time enables forecasting of inundation and the anticipation of hazardous events such as lava dome collapse (e.g., Vicari et al., 2011; Pallister et al., 2013, 2019; Pederson et al., 2017; Carr et al., 2019).

Probabilistic hazard maps can enable appropriate land-use planning policies before eruption avoiding development in areas with high probability of inundation (Tsang and Lindsay, 2020).

Attempts during ongoing eruptions to halt or divert flows (by erecting barriers, spraying lava with water, or breaking the margins of lava channels) have had mixed success (e.g., Barberi and Carapezza, 2004) nevertheless, in Hawaii, barriers have been constructed alongside new high value assets (Tsang and Lindsay, 2020). Evacuation remains the most effective strategy for protecting life and health from primary and secondary hazards (Tsang and Lindsay, 2020).

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Coordinating agency or organisation

International Association of Volcanology and Chemistry of the Earth's Interior) (IAVCEI) /Global Volcano Model (GVM) / International Volcanic Health Hazard Network (IVHHN).

GH0010 / **GEOHAZARDS / Volcanogenic (Volcanoes and Geothermal)**

Ash/Tephra Fall (Physical and Chemical)

Definition

Tephra is a collective term for fragmented magma and old (i.e., pre-existing) rocks ejected into the atmosphere from volcanic vents during an explosive eruption, irrespective of size, composition and shape (BGS, no date). The term 'volcanic ash' refers to the finest particles of tephra (less than 2 mm diameter).

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Annotations

Synonyms

Lapilli, Pyroclast, Blocks, Bombs.

Additional scientific description

The term 'volcanic ash' is often used loosely to include larger fragments, more correctly termed 'lapilli' (2 to 64 mm in diameter). The largest tephra clasts (> 64 mm) are called blocks and bombs. Fragments of all sizes generated during fragmentation of magma and lava are also known as 'pyroclasts', whether they travel through the atmosphere or are directly entrained in lateral moving flows.

Along with emissions of gas, tephra is the most frequent and widespread volcanic hazard. It is ejected into the atmosphere and transported laterally by wind and/or lateral gravitational spreading of umbrella clouds before falling out under gravity. Fine tephra (mainly volcanic ash) also rises convectively above pyroclastic density currents and lava fountains (Bonadonna et al., 2015, 2021; Jenkins, 2015). Tephra can affect very large areas; volcanic ash can remain airborne for days and can be transported for thousands of kilometres and may disrupt air traffic. Blocks and bombs mostly follow a ballistic trajectory, and so are not strongly affected by wind; nonetheless, the smallest blocks can also be entrained within convective plumes impacting a larger area than ballistic clasts. Tephra can cause fatalities directly, owing to ballistic impact, and indirectly due to collapse of buildings (mostly roofs) and trees due to tephra load. In addition, public health threats, clean-up and disruption to critical infrastructure services, aviation and primary production can lead to substantial societal impacts and costs, even at thicknesses on the ground of a few millimetres. Hot tephra (e.g., large lapilli and blocks and bombs) can also trigger fires if falling on ignitable material (e.g., dry vegetation, wooden structures). Intense tephra fall reduces visibility and may cause complete darkness during daylight hours, creating significant hazards for driving, for example (USGS, no date).

Lightning may be generated by friction between the fine airborne particles, which can be localised above the volcano or accompany large ash plumes as they move downwind. The impacts can be experienced across wide areas and can be long-lived, since eruptions can last from hours to years (IVHHN, 2021).

Tephra-fall deposits may also be the source of secondary hazards (e.g., lahars) and can be remobilised into the atmosphere by wind, traffic and human activities, prolonging the impacts. Tephra varies in appearance depending upon the composition of the magma and the style of the eruption (Bonadonna et al., 2015).

Various analytical and numerical models have been developed that forecast tephra dispersal and deposition from the finest fractions to ballistic blocks (e.g., Folch, 2012; Bonadonna et al., 2015; Biass et al., 2016; Osman et al., 2019). The International Civil Aviation Organization (ICAO) leads operational forecasting of ash cloud transport for the benefit of the aviation sector (ICAO, 2012; Lechner et al., 2017).

To assess severity at a site, tephra falls are most commonly described (e.g., eyewitness accounts) or measured according to their thickness. Increasingly though, loading (mass per unit area; kg/m2) is more informative for assessing impact to structures and agriculture, and enables consideration of water saturation (Jenkins et al., 2015). For respiratory health exposure and hazard assessment, monitoring of airborne concentrations of fine particulates is preferable, alongside physicochemical and toxicological characterisation of the ash particles (e.g., Horwell et al., 2013).

There were 52 recorded fatal incidents as a result of tephra (not including ballistics) between 1500 AD and 2017 resulting in 4315 fatalities and these occurred between 0.5 and 170 km from the source volcano at a median distance of 10 km (Brown et al., 2017). Over the same period, there were 57 fatal incidents due to ballistics, with 367 recorded fatalities 0 to 7 km from the volcanic source (Brown et al., 2017).

Approximate tephra thicknesses (hazard intensities) that relate to key damage and functionality states for a range of building types, critical infrastructure and agricultural categories are given by Jenkins et al. (2015).

Metrics and numeric limits

Not applicable.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Tephra particles can have acid coatings which may react with rain to damage vegetation and cause corrosion. The acid coating is rapidly removed by rain, which may then pollute local water supplies. Tephra can increase river turbidity leading to environmental problems.

Finer particles of ash may irritate the lungs and eyes (humans and animals) and exacerbate the symptoms of existing respiratory conditions (e.g., asthma and bronchitis) (Horwell and Baxter, 2006; IVHHN, 2020a).

In most eruptions, volcanic ash causes relatively few health problems, but generates much anxiety. However, there is insufficient evidence to be certain whether ash can trigger chronic diseases such as lung cancer and silicosis (if crystalline silica is a major component) (Horwell et al., 2012; IVHHN, 2020a), and all fine particulate matter (e.g., PM2.5) is considered to negatively impact mortality and morbidity, particularly for respiratory and cardiovascular diseases (WHO, 2013).

Livestock should ideally be under cover during tephra falls and veterinary services may be needed for respiratory, ingestion, eye and dental problems (USGS, 2020).

Medical services can expect an increase in the number of patients with respiratory and eye symptoms during and after a tephra-fall event, which can be measured by existing syndromic surveillance or by application of the International Volcanic Health Hazard Network standardised epidemiological protocols (IVHHN, 2020b; Mueller et al., 2020).

The fertility of the soils around many volcanoes is due to the weathering of old ash deposits, and the addition of thin tephra falls to soil can be beneficial in the long term. In many cases though, volcanic ash needs to be removed from urban and agricultural areas to prevent remobilisation and repeated impacts, as well as to prevent it from washing into drainage networks. Therefore, sites need to be identified to dispose of the ash, preferably before an eruption. Cleaning tephra from roofs, roads, agricultural land, and critical infrastructure may require significant volumes of water, trucks, diggers, etc., and can have significant associated costs (Hayes et al., 2015).

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Coordinating agency or organisation

International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, Global Volcano Model network (GVM) and International Volcanic Health Hazard Network (IVHHN).

GH0011 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Ballistics (Volcanic)

Definition

Ballistics comprise fragments of magma and old (i.e., pre-existing) rocks ejected during an explosive eruption at variable velocity and angle on cannon ball-like trajectories; they are not entrained within the volcanic plume and are dispersed in proximity to the vent (typically <5 km) (adapted from Biass et al., 2016 and Bonadonna et al., 2021).

References

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Annotations

Synonyms

Projectiles.

Additional scientific description

Ballistics may be a few centimetres to several metres in diameter. In most cases, the range of ballistics is a few hundred metres to 5 km, but they can be thrown to distances over 10 km in the most powerful explosions (Blong, 1984). Some blocks and bombs (i.e., tephra clasts >64 mm) can also be entrained within the volcanic plume and sedimented at larger distances than ballistics (Osman et al., 2019).

Fragments of all sizes generated during fragmentation of magma and lava are also known as 'pyroclasts' whether they travel through the atmosphere or are directly entrained in lateral moving flows.

Various analytical and numerical models have been developed that forecast ballistic dispersal (e.g., Fitzgerald et al., 2014; Biass et al., 2016).

Primary hazards. The high kinetic energies of ballistics when they land makes them hazardous to people, buildings, infrastructure and other assets. Ballistics may be ejected at over 300 m/s but slow down during flight, with terminal velocities typically <150 m/s (Walker et al., 1971). Impact energy (kinetic energy at the moment of impact) is strongly controlled by the size of a ballistic because this limits both its terminal velocity and mass (Williams et al., 2017). Alatorre-Ibargüengoitia et al. (2012) modelled impact energies of ballistics 0.2–0.6 m in diameter during small explosive eruptions (VEI 2–3) to be up to 106 J, well over the threshold required to penetrate reinforced concrete slabs (Jenkins et al., 2014).

Fragments of lava can be over 1100°C so, although they cool during flight, they may retain sufficient thermal energy on landing to burn certain building materials or other flammable materials (Vanderkluysen et al., 2012).

Secondary hazards. Ballistics may cause indirect fatalities and damage owing to the collapse of buildings (mostly roofs) or damage to infrastructure (power, roads). Hot ballistics can start fires if falling on ignitable material (e.g., dry vegetation, wooden structures).

Intense volcanic explosions that generate ballistics may cause shock and infrasonic waves in the atmosphere, which can shatter windows and damage delicate equipment (e.g., electronic doors) at distances of several kilometres from the volcano.

Ballistics and other loose fragmentary material may be remobilised in lahars or landslides.

Metrics and numeric limits

Not applicable.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Ballistics are associated with all types of explosive volcanic eruption (Fitzgerald et al., 2017). Explosions may be sudden with no precursory signs, especially if triggered by steam interaction with hot rocks or magma. Tourists and scientists have proven particularly vulnerable to unexpected explosive eruptions, as they tend to get close to volcanic vents. The sudden explosion of Mount Ontake, Japan, on 27 September 2014, resulted in the deaths of 58 hikers, 56 of whom were killed by ballistic rocks (Oikawa et al., 2016; Tsunematsu et al., 2016).

There were 57 fatal incidents due to ballistics between 1500 AD and 2017, with 367 recorded fatalities 0–7 km from the volcanic source (Brown et al., 2017). Many more people have been injured due to ballistic impacts, frequently suffering from blunt force trauma (broken bones), lacerations, burns, abrasions and bruising (Blong, 1984; Baxter and Gresham, 1997).

The high kinetic and thermal energy of ballistics can cause damage to buildings, infrastructure, agriculture and the environment through knock down, puncturing, crushing, burning and melting (Fitzgerald et al., 2017).

There have been studies of impact energy thresholds to perforate buildings (Blong et al., 1981; Pomonis et al., 1999) and the first fragility functions were presented by Biass et al. (2016). A combination of field data and experiments are enabling building design recommendations for emergency situations, but reducing exposure to ballistics is the best risk reduction measure (Williams et al., 2017).

As with other volcanic hazards, a combination of probabilistic volcanic hazard assessment and risk assessment combined with effective communication among scientists, emergency managers, local communities and other stakeholders can lead to effective management of risk (Fitzgerald et al., 2017).

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Coordinating agency or organisation

IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) / GVM (Global Volcano Model network) / IVHHN (International Volcanic Health Hazard Network).

GH0012 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Pyroclastic Density Current

Definition

Pyroclastic density currents are hot, fast-moving mixtures of volcanic particles and gas that flow according to their density relative to the surrounding medium and the Earth's gravity. They typically originate from the gravitational collapse of explosive eruption columns, lava domes or lava-flow fronts, and from explosive lateral blasts (adapted from Branney and Kokelaar, 2002 and Cole et al., 2015).

References

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Annotations

Synonyms

Pyroclastic flow, Nuée ardente, Ash flow, Hot avalanche.

Additional scientific description

The following terms may be considered sub-types of pyroclastic density currents (PDCs): pyroclastic flow, block-and-ash flow, pumice flow, lateral blast, pyroclastic surge. The pyroclastic flow and surge are two end members (dense and dilute end, respectively). The term 'ignimbrite' is commonly used as a general term describing pumice- and ash-rich PDC deposits of very varied volumes (Druitt, 1998; Branney and Kokelaar, 2002), but has also been used to refer, predominantly, to the large-volume end of this spectrum (e.g., Wilson and Hildreth, 2003).

PDCs are produced from volcanic eruptions across many orders of magnitude, from small-volume events (<0.001 to 1 km3) to caldera-forming eruptions with volumes around 101–103 km3 of erupted material (Druitt, 1998; Dufek et al., 2015). PDCs are hot, unstoppable, gas-particle mixtures that move extremely quickly across the ground surface at velocities of tens to hundreds of kilometres per hour and have temperatures of typically between 200 and 600°C (Cole, 2015; Dufek et al., 2015). Most PDCs propagate to distances of between a few to tens of kilometres from the source (Ogburn, 2012). For exceptionally large-magnitude events, PDCs may travel over 100 km and cover areas of up to 103–104 km2 (Takarada and Hoshizumi, 2020). Many of the aforementioned variables can be used as hazard metrics for PDCs: flow speed, flow density, temperature, dynamic pressure, flow and deposit thickness, maximum runout, invasion area, etc.

Two different flow parts commonly form PDCs: a dense, basal undercurrent dominated by particle-particle interactions; and a dilute, upper part whose motion is mainly dominated by turbulence (Branney and Kokelaar, 2002; Sulpizio et al., 2014; Cole, 2015). The dense basal part strongly interacts with (and is controlled by) the topographic surface as it erodes and deposits material along its path (Doronzo, 2012). The dilute upper part tends to be less controlled by topography and may decouple from the main dense undercurrent, overcoming topographic obstacles and following diverse propagation paths (e.g., Fisher, 1995; Ogburn et al., 2014). Extensive numerical modelling of PDCs has been conducted over recent decades, to better understand PDCs and quantify their hazard (Sulpizio et al., 2014; Dufek et al., 2015). Most past efforts have focused on simulating either the dense basal (e.g., Patra et al., 2005) or the dilute upper part of PDCs (e.g., Bursik and Woods, 1996), but several multiphase flow models have also been presented (e.g., Suzuki et al., 2005).

Between 1500 and 2017 AD, PDCs were the most deadly of all volcanic hazards: there were 102 fatal incidents and 59,958 fatalities caused directly by PDCs. 50% of PDC fatalities were recorded up to 10 km from a volcano and 90% up to 20 km (Brown et al., 2017). The 1883 eruption from Krakatau volcano (Indonesia) resulted in PDC fatalities up to 80 km from the volcano, aided by the passage of PDCs over the sea (Carey et al., 1996).

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

PDCs can kill all living things and destroy structures by abrasion, impact, burial and heat.

Risk to building structures has not been systematically assessed but dense PDCs can bury buildings and destroy their openings (windows, doors) and, in dilute PDCs, dynamic pressures of a few kilopascal can cause moderate to heavy damage to buildings (Valentine, 1998; Zuccaro et al., 2008).

Deaths commonly result from thermal injury (including laryngeal and pulmonary oedema), asphyxiation and impact or blast trauma (Baxter, 1990). Survivors of PDC inundation can suffer from severe burn injuries requiring specialist treatment (Loughlin et al., 2002).

Indirect casualties can include accidents, for example related to evacuation or unsafe driving conditions, heart attacks and cascading hazards such as fires, famine and disease. Indirect deaths can dwarf the numbers of direct deaths (Brown et al., 2017).

High resolution (spatial and temporal) monitoring of lava-dome extrusion rates, and topography, can enable dome collapse PDCs to be anticipated, resulting in timely evacuation (Pallister et al., 2013). Probabilistic volcanic hazard assessments of PDCs (e.g., Sandri et al., 2018) are increasing in number and methods are improving.

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Coordinating agency or organisation

International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) / Global Volcano Model (GVM) / International Volcanic Health Hazard Network (IVHHN).

GH0013 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Debris Flow/Lahars/Floods

Definition

Lahars are discrete, rapid, gravity-driven, water-saturated flows containing water and solid particles of volcanic rock, sediment, ice, wood, and other debris that originate at volcanoes (Gudmundsson, 2015; Vallance and Iverson, 2015).

References

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Annotations

Synonyms

Debris flow, Volcanic mudflow.

Additional scientific description

Lahars are sometimes referred to as debris flows and colloquially as volcanic mudflows. The word 'lahar' is a generic term for a complex flow phenomenon encompassing a wide range of flow types with different physical parameters. Sub-glacial eruptions can produce floods and lahars, known as 'Jökulhlaups' in Iceland (Gudmundsson, 2015).

Lahars can be extremely mobile, flowing at high speeds on steep volcanic terrains and for long distances (tens of kilometres) along valleys. A single lahar can consist of multiple alternating phases of flow with differing characteristics (Vallance and Iverson, 2015).

Lahars are typically topographically confined flows, so existing channel networks often control the dominant flow routing. However, lahars can be much larger than typical streamflows (both in the depth of the flow and the flow rate) so that overbank-ing is possible for lahars. Lahars are generally categorised as primary (syn-eruption) and secondary (post-eruption) (Vallance and Iverson, 2015).

Primary lahars are caused directly by volcanic eruptions through a range of processes including the disruption of crater lakes, the melting/erosion of glacial ice and snow by volcanic flows (e.g., pyroclastic density currents), the mixing of tephra with rain and ground water, and the incorporation of ground water into debris avalanches. Primary lahars may be hot for an extended time during their motion (Pierson and Major, 2014).

Secondary lahars occur due to the remobilisation of erupted pyroclastic deposits, often during intense and/or long-lasting rainfall, as a volcano's drainage system responds to the surface deposits added during eruptions and can continue for many years after an eruption with a decreasing frequency over time (Pierson and Major, 2014).

However, eruptive activity and secondary lahars can occur contemporaneously during long-lived eruptions at persistently active volcanoes.

Measurable and modellable parameters include flow speed, flow density, temperature, dynamic pressure, flow and deposit thickness, maximum runout, area of invasion, triggering factors (e.g., rainfall), solids volume concentration, eroded depth, friction coefficients.

There is little correlation between the magnitude of an eruption and the volume of primary lahars. An example is the 1985 eruption of Nevado del Ruiz, Colombia, which was a relatively small eruption in terms of erupted volume, but pyroclastic density currents flowing over an extensive summit ice and snow cap resulted in substantial glacial and snow melting (2×107 m3), initiating large (peak discharge <48,000 m3/s), fast (<17 m/s) lahars simultaneously in several drainages (Pierson et al., 1990). The devastating consequences included the loss of more than 24,000 lives (Brown et al., 2017). The magnitude of secondary lahars is dependent on rainfall intensity and duration, as well as sediment availability, so the largest lahar can occur a long time (possibly years) after an eruption (Pierson and Major, 2014).

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

The impact of lahars varies greatly depending on the flow type and magnitude, the weather conditions, the geomorphology, and the characteristics of the exposed assets. Fatalities are caused by burying, impact injury or drowning. There were 72 fatal incidents as a result of lahars between 1500 AD and 2017, with a total of 49,938 fatalities that occurred between 1 and 100 km from the source volcano (Brown et al., 2017). Infrastructure (including critical facilities), personal property, agricultural lands and livestock can be destroyed, buried or damaged. Lahars can erode and remove top-soils from farmlands.

Emergency response and clean-up can be difficult due to the material left behind by lahars. Lahar hazard mitigation has included evacuation before eruptions or storms, channel and dam engineering, land management and early warning systems (Pierson et al., 2014). Mapping the possible paths and dynamics of lahars can help to identify exposed communities and assets. The strong topographic control means that simple flow routing models (e.g., Iverson et al., 1998) can be effective, although models that incorporate flow dynamics provide additional useful information such as arrival time and dynamic pressure (Manville et al., 2013).

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Coordinating agency or organisation

International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), Global Volcano Model network (GVM) and International Volcanic Health Hazard Network) (IVHHN).

GH0014 / **GEOHAZARDS / Volcanogenic (Volcanoes and Geothermal)**

Landslide (Volcanic Trigger)

Definition

A landslide is the downslope movement of soil, rock and organic materials under the effects of gravity, which occurs when the gravitational driving forces exceed the frictional resistance of the material resisting on the slope. Landslides could be terrestrial or submarine (Varnes, 1978).

Reference

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Annotations

Synonyms

Mass movement, Mass wasting, Slip.

Additional scientific description

The term 'landslide' encompasses five modes of slope movement: falls, topples, slides, spreads, and flows. These are subdivided according to the type of geological material (bedrock, debris, or earth). Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope.

Landslides are common on volcanic cones because they are tall, steep, and weakened by the rise and eruption of molten rock. Magma releases volcanic gases that partially dissolve in groundwater, resulting in a hot acidic hydrothermal system that weakens rock by altering minerals to clay (USGS, no date).

Volcano landslides (debris avalanches) range in size from less than 1 km3 to more than 100 km3 (USGS, no date). They comprise masses of rock, soil and snow that are mobilised when the flank of a volcano collapses and slides downslope. The mobilised sediment can be very destructive and entrain more sediment (as well as vegetation or structures) along its path. The high velocity and momentum allows them to cross valleys and run up slopes several hundred metres high. The larger landslides are generally more deep-seated, involving weak hydrothermal and magmatic systems in the volcano.

The landslides leave a hummocky terrain that reflects the initial structure of the edifice (de Vries and Davies, 2015). The sediment largely comprises unsorted and unstratified angular-to-subangular debris (Siebert, 1996). Runout lengths are commonly many times the height of the volcano. Many landslides contain or incorporate water that leads to secondary debris flow and lahar generation. Runout varies with the extent of air or fluid entrainment; however, the physical basis of the long runouts is not fully understood. Most are the result of several factors, including volcanic flank failures. Landslides on volcanic islands such as Hawaii, Reunion and Tristan da Cunha are characterised by long runout distances and volumes exceeding 1000 km3 (Hürlimann et al., 2000).

Metrics and numeric limits

Landslide movement is likely to be moderate in velocity (1.5 metres per day) to extremely rapid. With increased velocity, the landslide mass of translational failures may disintegrate and develop into a debris flow (Varnes, 1978). For example, the landslide at Mount St. Helens on 18 May 1980, with a volume of 2.5 km3, reached speeds of 50–80 m/s, with the energy to surge up and over a 400-m-tall ridge located about 5 km from the volcano (de Vries and Davies, 2015).

Key relevant UN convention / multilateral treaty

Not applicable.

Examples of drivers, outcomes and risk management

Landslides can be extremely destructive, especially when failure is large, sudden and (or) the velocity is rapid. Rock avalanches pose some of the most dangerous and expensive geological hazards in mountainous terrain. The Mount St Helens eruption was triggered by landsliding as a consequence of structural instability of the volcano. The eruption caused the death of 57 people, 53 through direct impacts including asphyxiation, thermal injuries, and trauma. Snowmelt led to extensive river flooding (Oregon State University, 2020).

As well as the potential to trigger hydrothermal or magmatic eruptions and if the debris avalanches enter water bodies, tsunami may be generated (de Vries and Davies, 2015). As with other types of landslide, rock avalanche can cascade to form river dams with the potential for subsequent release and flooding.

The size of volcanos is such that remote sensing techniques can be used for monitoring, for example, GPS, aerial photography, and satellite imageries including InSAR (radar). At the local scale, ground-based techniques such as LiDAR and seismometers can be deployed (Moss et al., 1999; Highland and Bobrowsky, 2008) with varying degrees of success.

While the physical damage of landslides is well documented, health impacts are complex. The risk of an increase in infectious diseases is of concern during the response and recovery phase after any major disaster. Displacement of people due to the destruction of their homes and other infrastructure can place them in unfamiliar surroundings, which, if they conflict with traditional beliefs and practices with regard to water supply and hygiene, can result in unsafe behaviours. The medium- to long-term effects of changes to the environment caused by landslides, such as deforestation, and changes to river courses, can increase the risk of vector-borne diseases, and as a result, the health impacts can extend long after the initial disaster is over. Disruption of soil can also increase exposure to infectious organisms (Kennedy et al., 2015).

The psychosocial and mental health impacts on survivors and rescue personnel from landslides are increasingly recorded (e.g., Oregon State University, 2020). The prevalence of psychiatric disorders and wider support needed to reduce misuse of substances has been identified (Kennedy et al., 2015; Dell'Aringa et al., 2018).

Increasingly, the science of landslide physics is allowing the nature of these hazards to be understood, which is leading to better techniques through which they can be managed and mitigated.

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Coordinating agency or organisation

British Geological Survey.

GH0015 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Ground Shaking (Volcanic Earthquake)

Definition

Ground shaking is the movement of the Earth's surface from earthquakes. Ground shaking is produced by waves that travel through the earth and along its surface (USGS, no date).

A volcanic earthquake is any earthquake that results from tectonic forces which occur in conjunction with volcanic activity (UN-SPIDER, no date).

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Annotations

Synonyms

Ground movement, Ground motion, Ground acceleration, Ground velocity.

Additional scientific description

Seismic activity is a common feature of volcanic eruptions. Often, there are many thousands of earthquakes recorded during an eruption. Most volcanic earthquakes are small but significant (moderate and large) volcanic earthquakes do occur (Zobin, 2001). Volcanic earthquakes, like all earthquakes, can cause shaking, damage to buildings and other structures, as well as changes in the surrounding environment. This shaking depends on the size of the earthquake, the distance from the source and the soil conditions (Bormann et al., 2013).

Metrics and numeric limits

The size of a volcanic earthquake is measured using the same magnitude scales as other earthquakes.

Magnitude is not a direct measure of ground shaking but, along with the distance from the earthquake source and geological conditions, decides the shaking at any point. There are many magnitude scales, but they should all yield approximately the same value for any given earthquake (USGS, no date). During the 20th century there were three large (magnitude greater than 7) earthquakes directly associated with volcanic eruptions (Zobin, 2001).

The effect of ground shaking on people and buildings is characterised by its macroseismic intensity. The three most important intensity scales in current use are the European Macroseismic Scale (EMS-98), the Modified Mercalli Scale (MM or MMI) and the JMA scale (Musson and Cecić, 2013). These scales rate the shaking at a given point by the observed effects, ranging from not felt to total damage (e.g., Grünthal, 1998). A magnitude 7 earthquake would be expected to have an intensity, near to the epicentre, of about EMS-98 9 (normally written IX to avoid confusion with magnitude). This is described by the scale as 'Destructive' with the description 'Many weak constructions collapse. Even well-built ordinary buildings show very heavy damage' (Grünthal, 1998).

Instrumental measures of shaking include peak ground velocity (PGV) and peak ground acceleration (PGA). Although it has been found that earthquake damage is much more closely correlated with PGV than with PGA (Wu et al., 2003), PGA continues to be the more used of these parameters. An often used relationship between intensity and PGA and PGV (Wald et al., 2019) suggests that shaking below 0.0005 g or 0.002 m/s will not be felt and that above 0.4 g or 0.4 m/s structural damage can be expected. A magnitude 7 earthquake could be expected to cause ground shaking of over 0.8 g or 0.9 m/s near the epicentre.

Key relevant UN convention / multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Volcanic seismicity is often the first sign of a volcanic eruption. It can also occur at a volcano which does not subsequently erupt (Sparks, 2003).

Ground shaking on volcanoes is more likely to result in secondary hazards than elsewhere. These include landslides, lahars and pyroclastic density currents. Aggravating factors are the time of the event and the number and intensity of aftershocks. Compound hazards include fire and tsunami (WHO, no date).

A community can mitigate ground shaking damage by adopting and enforcing a building code with appropriate seismic design and construction standards (FEMA, 2010).

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Coordinating agency or organisation

British Geological Survey.

GH0016 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Volcanic Gases and Aerosols

Definition

Volcanic gas includes any gas-phase substance that is emitted by volcanic or volcanic-geothermal activity. Volcanic aerosols include liquid or solid particles that are small enough to be suspended in the air, and that are emitted by volcanic or volcanic-geothermal activity (adapted from Baxter and Horwell, 2015, Fischer and Chiodini 2015, and Williams-Jones and Rymer 2015).

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Annotations

Synonyms

Volcanic gases: Vapours, Volatiles, Fumes.

Aerosols: Particles, Droplets, Particulate matter, PM. Vog (a term for volcanic gas and aerosol air pollution, used mostly in Hawaii).

Additional scientific description

Volcanic gases can be emitted directly into the atmosphere from magma or by magma interacting with crustal rocks. They can be observed with spectroscopic instruments from ground and space, and their future dispersion can be modelled, allowing forecasts of gas and aerosol concentrations to be made. Volcanic gas composition and concentrations can be modified through interaction with ground or surface waters; gases generated by heating and vaporising groundwater in volcanic-geothermal areas. Volcanic gases can also remain pressurised in the subsurface or within lakes (Oregon State, no date).

Volcanic aerosol sizes range from a few nanometres (nm) to several hundred micrometres (μm). Volcanic aerosol refers to particles formed through condensation of volcanic gases, or through reaction of the gases with the atmosphere and sunlight and is thereby distinct from 'ash' or 'tephra' that is formed through fragmentation of magma or lava. Aerosols can be in liquid or solid form and evolve between these states with time (Oregon State, no date).

Volcanic gases and aerosols are emitted by almost any type of volcanic activity:

- Emissions from explosive eruptions: Depending on the explosive power, emissions can be injected into the stratosphere or stay in the troposphere and spread around the globe in the most powerful events. Typical emission duration is hours to days (Rose and Durant, 2009).

- Emissions from effusive lava eruptions, open vents and lava lakes: Emission durations can last from days up to several decades or longer. Emissions are typically confined to the troposphere and have been instrumentally detected up to thousands of kilometres from the source (Rose and Durant, 2009).
- Emissions from crater lakes, and volcanic-geothermal systems: These low-energy and relatively low-temperature emissions (typically <100°C) are usually confined to the immediate vicinity of the source. However, large and highly hazardous emissions can occur if gases accumulate in the bottom of a lake and then rapidly release (Schmid et al., 2005).

The chemical composition of volcanic gas and aerosol emissions is highly heterogeneous. The composition changes continuously as the emissions drift away from their source and react with the atmosphere and sunlight. Typically, the most abundant volcanic gas is water vapour (80% or more of the gas mass). Other common gases are carbon dioxide (CO2), sulphur dioxide (SO2), hydrogen sulphide (H2S) and hydrogen halides (hydrogen chloride [HCl] and hydrogen fluoride [HF]). Radon and carbon monoxide (CO) are also emitted in trace amounts (Oregon State, no date).

Aerosol forms by condensation of volcanic gases, both near-instantaneously after emission, and on the timescale of hours to days. Sulphate, a common aerosol component, forms through conversion of SO2 gas. Aerosol contains a variety of trace components, including elements collectively classified as metal pollutants by environmental and health protection agencies (Oregon State, no date).

The abundance of emitted volcanic gases and aerosol varies greatly among eruptions. Recent large eruptions of Holuhraun in Iceland 2014–2015 and Kīlauea Hawaii in 2018, emitted as much SO2 per day as anthropogenic activities in China (50–200 kt/day) over several months (Pfeffer et al., 2018; Kern et al., 2020). A larger-scale emission scenario, which may occur in the coming decades or centuries, includes a 'Laki-type' eruption in Iceland which can emit ten times more SO2 than the recent eruptions described above. There are tens, or potentially hundreds, of volcanoes worldwide which emit smaller amounts of SO2 (0.5–5 kt/day) (Carn et al., 2016) but sustain the emissions over years-to-decades (e.g., Mt Etna; Aiuppa et al. 2008).

Volcanic gas and aerosol exposure is listed as the cause of 1% of total volcanic hazard fatalities (2283 people; Brown et al., 2017). This estimate includes only fatalities due to extreme direct exposure and does not include premature mortality caused by long-term air and environmental pollution. It has been estimated that 800 million people live within 100 km of a volcano that has erupted in the last 10,000 years (Auker et al., 2013), a range within which they could be exposed to this hazard.

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and control measures of the hazard

SO2, particulate matter <2.5 μm in diameter (PM2.5) and, in some cases, H2S, are the only volcanic gas and aerosol pollutants that are monitored and forecasted operationally. The monitoring and forecasting capacity is present almost exclusively in high-income countries where the emission source is located (e.g., US, Japan, Italy, Iceland). The impacts of volcanic gas/aerosol emissions on air quality and human health are challenging to constrain and are generally absent from local hazard assessments and mitigation plans in lower-income countries.

Multiple chemical species in volcanic gases and aerosols may cause a human and/or environmental impact.

- Health impacts: The common effects of volcanic gases, in particular SO2, H2S, HCl and HF are: (i) irritation to the respiratory tract, eyes and skin; (ii) chest tightness, shortness of breath, and headaches; and (iii) asthma aggravation. SO2 is the greatest respiratory hazard, causing health impacts, especially for asthmatics, up to thousands of kilometres from the source. High concentrations of fluoride (from HF) causes damage to teeth and bones; it is especially dangerous to grazing animals. All of the listed gas species, as well as CO2 and CO, can cause death in high concentrations. Volcanic aerosol is typically PM2.5, an air pollutant with no known safe exposure limits (WHO, 2013a). Both acute and chronic exposure to PM2.5 causes respiratory and cardiovascular morbidity and premature mortality (WHO, 2013b). More information on the health hazards and impacts of volcanic gases and aerosols can be found on the International Volcanic Health Hazard Network website (IVHHN, 2020a).
- Environmental impacts: Acid rain is commonly caused by mixing of atmospheric water with volcanic gas and aerosol and leads to degradation of plant health and diversity, crop damage and damage to infrastructure. Metal pollutants can contaminate rainfall and accumulate in soils, surface waters and plants (Bourassa et al., 2012).
- Climate impacts: Large explosive eruptions can form an aerosol blanket in the stratosphere which leads to cooling at the surface of ~0.5°C. The effect may last for about 2 years (Bourassa et al., 2012).

Owing to the multiple impacts of volcanic gases, agencies in Hawaii provided a public dashboard which summarises the various impacts as well as providing access to monitoring and forecasting data (IVHHN, 2020b). The dashboard was accessed more than 50,000 times per week during the 2018 Kīlauea volcanic crisis.

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Coordinating agency or organisation

International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) / (Global Volcano Model (GVM) / International Volcanic Health Hazard Network (IVHHN).

GH0017 / **GEOHAZARDS / Volcanogenic (Volcanoes and Geothermal)**

Tsunami (Volcanic Trigger)

Definition

Volcano tsunamis (pronounced soo-ná-mees), are a series of waves created when water surrounding a volcano is displaced following an eruption, a landslide, or failure of a volcanic edifice into surrounding water. If the generating mechanism is large enough, the waves can be significant on local, regional or even transoceanic scales (Day, 2015).

Reference

Day, S., 2015. Volcanic Tsunamis. The Encyclopedia of Volcanoes, 2nd Ed.

Annotations

Synonyms

Not found.

Additional scientific description

Tsunami is the Japanese term meaning wave ('nami') in a harbour ('tsu'). Tsunamis are a series of gravity waves of extremely long (up to hundreds of kilometres) length with periods of 10 to 60 minutes that can travel across ocean basins with little loss of energy. They are usually generated by earthquakes occurring below or near the ocean floor. Approximately 80% of tsunamis are caused by earthquakes, but also by volcanic eruptions, submarine landslides, and coastal rock falls. Tsunami waves, on entering shallow water steepen and increase in height attaining elevations (or runups) of tens to hundreds of meters, inundating low-lying areas and, where local submarine topography causes the waves to steepen, they may break and cause great damage. Tsunamis have no connection with tides; the popular name, tidal wave, is entirely misleading (IOC, 2019).

Volcanic tsunamis are defined as those with source mechanisms from erupting and quiescent volcanoes, and include explosions, pyroclastic flows and lahars entering the water, earthquakes preceding or during a volcanic eruption, flank failure (from rock falls to massive debris avalanches), collapse of coastal lava benches, caldera collapse and shock waves from large explosions. Of these mechanisms, only pyroclastic flows, flank failures and caldera subsidence generate damaging tsunamis, as their volumes are larger than one km3. Wavelengths of volcanic tsunamis are shorter than those from earthquakes and undergo more rapid dispersion during propagation. These tsunamis are more hazardous on coastlines close to the volcano. Because of the different potential mechanisms and their possible interactions, numerical simulations of volcano tsunamis, and model-based assessments of hazards from volcano tsunamis, are challenging, compared to those from earthquakes (Day, 2015).

The Intergovernmental Oceanographic Commission (IOC) uses the following terms to assess the scale and impact of a tsunami (IOC, 2019):

- Travel time: Time required for the first tsunami wave to propagate from its source to a given point on a coastline.
- Arrival time: Time of the first maximum of the tsunami waves.
- Inundation or Inundation-distance: The horizontal distance inland that a tsunami penetrates, generally measured perpendicularly to the shoreline.
- Inundation (maximum): Maximum horizontal penetration of the tsunami from the shoreline. A maximum inundation is measured for each different coast or harbour affected by the tsunami.
- Inundation area: Area flooded with water by the tsunami.
- Inundation height Elevation reached by seawater measured relative to a stated datum such as mean sea level or the sea level at the time of tsunami arrival, at a specified inundation distance. Inundation height is the sum of the flow depth and the local topographic height. Sometimes referred to as tsunami height.

- Inundation line: Inland limit of wetting measured horizontally from the mean sea level line. The line between living and dead vegetation is sometimes used as a reference. In tsunami science, the landward limit of tsunami run-up.
- Leading wave: First arriving wave of a tsunami. In some cases, the leading wave produces an initial depression or drop in sea level, and in other cases, an elevation or rise in sea level. When a drop in sea level occurs, sea level recession is observed.
- Mean height: Average height of a tsunami measured from the trough to the crest after removing the tidal variation.
- Run-up
  - Difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami. In practical terms, run up is only measured where there is a clear evidence of the inundation limit on the shore.
  - Elevation reached by seawater measured relative to some stated datum such as mean sea level, mean low water, sea level at the time of the tsunami attack, etc., and measured ideally at a point that is a local maximum of the horizontal inundation. Where the elevation is not measured at the maximum of horizontal inundation, this is often referred to as the inundation-height.
- Tsunami amplitude: Usually measured on a sea level record, it is (1) the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level at the time, (2) half the difference between an adjacent peak and trough, corrected for the change of tide between that peak and trough. It is intended to represent the true amplitude of the tsunami wave at some point in the ocean. However, it is often an amplitude modified in some way by the tide gauge response.
- Tsunami period: Amount of time that a tsunami wave takes to complete a cycle, or one wavelength. Tsunami periods typically range from 5 to 60 minutes. Tsunami period is often measured as the difference between the arrival time of the highest peak and the next one measured on a water level record.
- Tsunami wavelength: The horizontal distance between similar points on two successive waves measured perpendicular to the crest. The wavelength and the tsunami period give information on the tsunami source. For tsunamis generated by earthquakes, the typical wavelength ranges from 20 to 300 km. For tsunamis generated by volcanic mechanisms wavelengths are much shorter than those from earthquakes, ranging from hundreds of meters to tens of kilometres.
- Meteotsunami: Volcanic eruptions, submarine landslides, and coastal rock falls can also generate tsunamis, as can a large meteorite impacting the ocean. Tsunami-like phenomena generated by meteorological or atmospheric disturbances.

For more terms see IOC (2019).

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Not found.

Examples of drivers, outcomes and risk management

Volcanic tsunamis are relatively infrequent, and unpredictable, hazards that are caused by rapid, mainly vertical, ground displacements (earthquakes and landslides) or eruptive activity at a volcano. Their hazard is mainly to coastal communities within a few tens of kilometres of active volcanoes, although more infrequent, larger volume, volcano flank collapse landslides, and explosive eruptions are a hazard at greater distances of hundreds of kilometres. At present, there is no defined management structure to mitigate the hazard because of the complex range of volcanic tsunami mechanisms. Through analysis of geological and historical evidence of past behaviour at a volcano, however, it is possible to identify volcanoes that generate tsunamis and investigate these to determine whether risk management measures (such as changes to coastal land use patterns) can be formulated. Monitoring volcanic activities and their local environments (for example ground stability and changes in ground motion), has the potential to identify imminent eruptive activity, or changes at a volcano (such as increased seismicity), that could make it more susceptible to instabilities, such as landslides or collapse, with the potential for initiating tsunamis. Thus, in contrast to risks from earthquake-generated tsunamis, that require management through rapid responses based on the detection of large magnitude events, the risks from volcanic tsunamis could, to some extent, be addressed by anticipatory measures, such as coastal evacuations, in response to increased volcanic activity, on which early warning system messaging is based (Day, 2015).

Primary hazards/damage. Damage and destruction from tsunamis are the direct result of three factors: inundation, wave impact on structures, and erosion. Deaths occur by drowning and physical impact or other trauma when people are caught in the turbulent, debris-laden tsunami waves. Strong tsunami-induced currents have led to the erosion of foundations and the collapse of bridges and seawalls. Floatation and drag forces have moved houses and overturned railroad cars (IOC, 2019:6).

Tsunami associated wave forces have demolished frame buildings and other structures. Considerable damage is also caused by floating debris, including boats, cars, and trees that become dangerous projectiles that may crash into buildings, piers, and other vehicles. Ships and port facilities have been damaged by surge action caused by even weak tsunamis. Fires resulting from oil spills or combustion from damaged ships in port, or from ruptured coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami (IOC, 2019:6).

Secondary hazards/damage. Secondary hazard/damage includes sewage and chemical pollution following the tsunami destruction. Damage to intakes, discharge, storage facilities and flooding of cooling generators are also major potential problems. During tsunami drawdown, there is the potential for the receding flood waters to uncover cooling water intakes associated with nuclear power plants, leading to overheating and explosion of nuclear facilities (IOC, 2019:7).

Environmental damage and damage to coastal croplands can result from deposition of sediments over inundated areas and salt water contamination. This could be a particular problem with tsunamis associated with volcanic eruptions, from the transport and deposition of floating pumice onto land, and the erosion, transport and redeposition of volcanic tephra deposited in phases of the eruption prior to the tsunami inundation. Clean-up efforts can be complicated by contamination of sediment and debris with salt and with spilt oil fuels and other chemicals.

Risk management for tsunamis includes a number of guidelines on tsunami risk assessment/management are available. Examples include IOC (2015) and UNDRR (2017).

Regional Coordination and Centres: The IOC is coordinating the implementation of a global tsunami warning system, building upon its experiences in the Pacific to establish regional warning systems for the Indian Ocean (IOTWMS); Caribbean Sea (ICG-CARIBE-EWS); and the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS). The regional systems coordinate international tsunami warning and mitigation activities, including the issuance of timely and understandable tsunami bulletins to IOC Member States.

The Intergovernmental Coordination Group for Tsunamis addresses tsunami risk globally through the following groups:

ICG-PTWS Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System, formerly ICG/ITSU, was renamed by Resolution EC-XXXIX.8 of the IOC Executive Council in 2006 as proposed by the International Coordination Group for the Tsunami Warning System in the Pacific at its 20th Session in 2005 (Recommendation ITSU-XX.1). There are presently 46 Member States in the ICG-PTWS. ICG/ITSU, the International Coordination Group for the Tsunami Warning System in the Pacific was established by Resolution IV-6 of the 4th Session of the IOC Assembly in 1965. The Pacific Tsunami Warning Center (PTWC) serves as the Tsunami Service Provider (TSP) for the Pacific Ocean. Other TSPs for specific regions of the Pacific Ocean are the North West Pacific Tsunami Advisory Center (NWPTAC) and the South China Sea Tsunami Advisory Center (SCSTAC). The ICG-PTWS presently comprises over 40 Member States and oversees warning system operations and facilitates coordination and cooperation in all international tsunami mitigation activities.

ICG-IOTWMS The Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG-IOTWMS) was formed in response to the tragic tsunami on December 26th 2004, in which over 230,000 lives were lost around the Indian Ocean region. The ICG-IOTWMS comprises 28 Member States. There are three TSPs in the Indian Ocean, hosted by the governments of Australia, Indian and Indonesia.

ICG-NEAMTWS The Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS) was formed in response to the tragic tsunami on 26 December 2004, in which over 230,000 lives were lost around the Indian Ocean region (Indian Ocean Tsunami Information Centre, no date). The ICG-NEAMTWS consists of Member States bordering the North-eastern Atlantic and those bordering and within the Mediterranean and connected seas. There are currently five accredited Tsunami Service Providers (France, Greece, Italy, Portugal, Turkey) in the NEAM region providing tsunami services and alerts to subscribing Member States.

ICG-CARIBE-EWS The Intergovernmental Coordination Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG-CARIBE-EWS) was established in 2005 and currently comprises 32 Member States and 16 Territories in the Caribbean.

Tsunami Service Providers (TSPs) are centres that monitor seismic and sea level activity and issue timely tsunami threat information within an ICG framework to National Tsunami Warning Centres (NTWCs) / Tsunami Warning Focal Points (TWFPs) and other TSPs operating within an ocean basin. The NTWCs / TWFPs may use these products to develop and issue tsunami warnings for their countries. TSPs may also issue public messages for an ocean basin and act as NTWCs providing tsunami warnings for their own countries. Currently there are nine operational TSPs.

National Tsunami Warning Centres (NTWCs) are a centre officially designated by the government to monitor and issue tsunami warnings and other related statements within their country according to established national Standard Operating Procedures.

World Tsunami Awareness Day, 5 November every year: The United Nations, through UN Resolution 70/203 adopted on 22 December 2015, has designated 5 November as World Tsunami Awareness Day (UNDRR, 2020). The day aligns with the International Day for Disaster Reduction (13 October) and the seven targets of the Sendai Framework for Disaster Risk Reduction 2015–2030 (ITIC, 2020). The IOC is a key international partner of the UNDRR on World Tsunami Awareness Day.

Tsunami Ready is a voluntary community recognition programme that promotes tsunami hazard preparedness as an active collaboration among federal, state/territorial and local emergency management agencies, community leaders and the public. The main goal of the programme is to improve public safety before, during and after tsunami emergencies. It aims to do this by establishing guidelines for a standard level of capability to mitigate, prepare for and respond to tsunamis, and working with communities to help them meet the guidelines and ultimately become recognised as 'tsunami ready' by the National Weather Service. It was first implemented in the United States .To date, there are 26 IOC-UNESCO Tsunami Ready recognised communities in 18 countries and territories, excluding those implemented in the United States.

Community engagement with evacuation zones and the 'blue lines' project In New Zealand, the Wellington Region Emergency Management Office has developed the Blue Line Project in collaboration with communities in Wellington's southern coastal suburbs. In this project, the local community helps to plan evacuation routes and safe locations based on indicative evacuation zone mapping, and blue lines are painted on the road surface at the maximum estimated tsunami inundation extent. Accompanying evacuation signage is installed. Community members are engaged early in the project, publicising the work and helping to develop blue line locations, evacuation zone maps and information boards. The communities participating in the Blue Line Project can be considered to have a higher degree of public education regarding tsunami evacuation than other communities (Fraser et al., 2016). Other communities around the world have used similar community engagement strategies.

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Coordinating agency or organisation

United Nations Educational, Scientific and Cultural Organization (UNESCO), Intergovernmental Oceanographic Commission (IOC-UNESCO) and the British Geological Survey.

GH0018 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Lightning (Volcanic Trigger)

Definition

Volcanic lightning is an electrical discharge caused by a volcanic eruption. It is typically associated with ash-rich eruption plumes but can also arise from a range of volcanic processes including ground-hugging ash flows and lava-ocean entry (adapted from Mather and Harrison, 2006; Behnke and McNutt, 2014; and McNutt and Thomas, 2015).

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Annotations

Synonyms

Dirty thunderstorm, Plume lightning, Vent discharges, Near-vent lightning.

Additional scientific description

Explosive injection of volcanic ash and gas into the atmosphere produces a wide range of electrical activity (Behnke and McNutt, 2014). The most hazardous electrical phenomenon is cloud-to-ground volcanic lightning, which creates a transient channel of hot plasma between a volcanic cloud and the ground. Exactly like ordinary thunderstorms, cloud-to-ground lightning from volcanic eruptions can produce thunder, trigger wildfires and destroy unshielded monitoring equipment or other infrastructure. Despite its potential impact, there are only a handful of documented cases where volcanic lightning resulted in injury or death (McNutt and Thomas, 2015).

In general, the hazards of volcanic lightning increase with eruptive intensity (McNutt and Williams, 2010; Behnke et al., 2013):

- Small eruptions: Low plumes (<1 km high) have been observed to create lightning (Cimarelli et al., 2016), including low-level steam plumes from lava flows entering the ocean. However, these flashes are sparse and only measurable with close-range sensors.
- Moderate eruptions: Slightly larger eruptions with plume heights 1–10 km (and ground-hugging ash flows if present) are likely to produce some lightning activity, but it tends to be weak and restricted to areas within about 20 km of the volcano (Behnke et al., 2013; Van Eaton et al., 2020).
- Large eruptions: Plumes exceeding heights of 10–15 km above the vent tend to produce the highest rates of volcanic lightning. These volcanic events occur only a few times per year worldwide, and in some instances are capable of transporting lighting-rich plumes over 100 km from the volcano (Van Eaton et al., 2016). Volcanic lightning from large eruptions is detectable on a global scale using worldwide networks.

The origin of volcanic plume electrification is a topic of active investigation, but it is clear that at least two distinct processes are involved. Silicate charging occurs close to the eruptive vent, during magma fragmentation and high-energy collisions among airborne rock particles (Mather and Harrison, 2006). At higher altitudes, ice charging—which is responsible for lightning in ordinary thunderstorms—becomes active if the volcanic plume rises well above the freezing level (approximately -20°C), creating a mixed-phase region of ice crystals, soft hail, and supercooled liquid water (Behnke et al., 2013; Van Eaton et al., 2020). Once the particles undergo either or both of these charging mechanisms, they accumulate in oppositely charged regions due to turbulent flow and gravitational separation of particles based on their different sizes and settling speeds (Behnke et al., 2013). Charge separation builds an electric field until it exceeds the local breakdown threshold of surrounding air, resulting in lightning discharges.

Metrics and numeric limits

Not identified.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

The hazards of cloud-to-ground volcanic lightning are nearly always of second-order importance compared to the other volcanic hazards of ground-hugging ash flows, lahars, and ashfall (Blong, 2000). The exception is rare situations when a large eruption transports a lightning-rich cloud directly over a populated area, exposing people and infrastructure to cloud-to-ground lightning. In areas of the world where ordinary thunderstorms are rare (e.g., high latitudes), the local population may not be accustomed to moving immediately indoors during lightning activity.

Current methods for mitigating this hazard include developing near-real time alerts for volcanic thunderstorms using global or regional networks of radio antennas (Behnke and McNutt, 2014).

A well-established example includes the World Wide Lightning Location Network's volcanic lightning monitor, which generates an alert when lightning initiates near an active volcano and progresses outward through time (University of Washington, no date) .

Detection of radio emissions from electrical discharges can provide early warning of a lightning-rich eruption because the signal travels at the speed of light.

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Coordinating agency or organisation

United States Geological Survey.

GH0019 / **GEOHAZARD / Volcanogenic (Volcanoes and Geothermal)**

Urban Fire (During/Following Volcanic Eruption)

Definition

Urban fires are fire involving buildings or structures in cities or towns with potential to spread to adjoining structures. Triggers of urban fires are numerous, from human actions (e.g., knocking over a candle) and technological triggers (e.g., power surge overloading appliances), to natural triggers (e.g., wildland fires interacting with urban areas). Triggers from volcanic eruptions include lava flows, pyroclastic density currents, tephra, and ground shaking (adapted from Baxter et al., 2005 and ISO, 2020).

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Annotations

Synonyms

Urban conflagration.

Additional scientific description

All fires, regardless of trigger, need three elements to sustain themselves: fuel, oxygen, and heat. The heat thermally decomposes (pyrolysis) the fuel into a hot gas (volatiles) which mixes with the oxygen which then creates a combustible gas namely the flame, the edge of which is where the combustion reaction happens. The flame can then transfer the heat through: radiation to other objects that it has a line of sight to; convection of hot gases; and conduction through the fuel that is pyrolysing (Drysdale, 2011).

Most cellulosic materials pyrolyse between 150 and 500°C to producing volatiles (Zhou et al., 2013). These volatiles will spontaneously ignite if the surface of the pyrolysing object reaches between 450 and 600°C, or between 300 and 450°C if there is a flame already present (Drysdale, 2011).

As the fire grows within a room, the rate at which fuel is consumed increases if there is sufficient oxygen within the room. If oxygen levels are low, then the fire will 'move' towards more oxygen-rich environments, this causes a phenomenon called flashover, where flames (typically about 1 m long under laboratory conditions for a standard door and a 9 m2 room) are ejected from compartment openings (Drysdale, 2011). In windier conditions, these can increase up to 3 m for a standard door-sized opening (de Koker et al., 2020), however this is not a linear relationship, and above a certain wind speed (dependent on the size of flame and other spatial and material properties) the length of the flame will not increase any further as convective cooling due to the wind reduces the amount of heat energy within the flame. If the spatial distribution of homes is close, then fires can spread from one building to another. The separation distance will be determined by the specific typology of the compartment/room, its openings, and the fuel therein.

Four areas should be considered in relation to fire triggered specifically by volcanic eruptions: lava flows, pyroclastic density currents (PDCs), hot tephra, and ground shaking.

- Lava flows: high temperature lava (1000–1200°C), moving usually in the order of 4–5 km/hr but exceptionally up to tens of kilometres per hour (e.g., the lava lake at Nyiragongo; Tedesco et al., 2007; Balagizi et al., 2018) may interact with combustible materials in its path and cause ignitions.
- Pyroclastic Density Currents: PDCs are hot, unstoppable, gas-particle mixtures that race across the ground surface at velocities of tens to hundreds of kilometres per hour and have temperatures typically between 200 and 600°C (Dufek et al., 2015). At these temperatures pyrolysis will occur for most cellulosic materials and fire damage will be observed (Baxter et al., 2005). The noxious gases often replace oxygen within the PDCs and this, combined with the flow speed which takes energy away from the pyrolysing surface (Babrauskus, 2003), limits the probability of ignition during the immediacy of the current. However, the energy stored in the materials and residual temperatures when oxygen is present can cause ignitions. PDCs can cause large amounts of structural damage creating openings and breaking of windows for hot ash to ingress and they can also redistribute fuel load (trees etc.) facilitating urban fire spread. PDCs can also cause ignitions in a similar manner to ground shaking (see below).
- Hot tephra: large lapilli, rocks and bombs, have the ability to cause ignition of dry combustible materials in and around urban structures, while the accumulation of hot volcanic ash (>300–400°C) could accumulate on surfaces to cause fires and as for fire brands created by wildfires, could ingress into structures through openings and cause ignitions (Baxter et al., 2005).
- Ground shaking: caused by the eruption and potential to be felt over large distances, ground shaking can unsettle open flames or disrupt energy supplies within buildings and could thus be a triggering event for a fire.

If fires are triggered in one or more rooms in a home, then homes can be severely affected by fire damage during/following a volcanic eruption.

Urban fires during/following a volcanic eruption have not been systematically recorded in detail to date. Baxter et al. (2005) have created a six-point damage scale which incorporates fire as an observed effect for PDCs.

Metrics and numeric limits

Not available.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Urban fires can cause large losses of life and livelihood: 95% of global deaths (180,000 to 300,000 people per year) and injury (10 million Disability-Adjusted Life Years lost each year) from fire occur in low and middle income countries (Mock et al., 2008; WHO, 2018); fire costs 1% of global GDP (The Geneva Association, 2014); and those who are at greatest risk (the urban poor) generally have little in means of protection against losses. In addition, those at greatest risk of death and injury are the old and the young due to lack of knowledge in how to respond and lack of mobility when trying to respond (Rush et al., 2020).

Urban fires are linked to density of structures and type of construction. Highly dense settlements (i.e., informal settlements or slums) are likely to have large areas of structures that are in close proximity to one another which will facilitate fire spread. This, when combined with combustible construction can lead to large-scale fire events. Combustible construction here refers not only to the material used in construction but also how the structure is sealed against the weather. For instance, a steel walled structure that has any gaps at joints sealed with paper or plastic materials would be susceptible to fire attack from another structure (Walls et al., 2017, 2018; Kahanji et al., 2019).

The density of settlements and the construction of the buildings is also inextricably linked to the wealth of the inhabitant with the urban poor being less able to live in space and less able to live in non-combustible buildings or to maintain buildings in such a way that fire events are more readily controlled. There are also areas, historic in nature, that have high structure density and combustible construction such as the fire in Shangri-La that occurred on 11 January 2014 (Associated Press, 2014).

Baxter et al., (2005) gave a good summary of urban fires known to have followed volcanic eruptions. Volcanic eruptions which create PDCs can break windows in homes. This will allow hot ash and other tephra to ingress the homes and, if combustible materials are present, can cause large fires to occur. The high temperatures of the PDCs can also pyrolyse and char roof structures. This was seen at the Montagne Pelée and St Vincent eruptions in 1902, Vesuvius in AD79, Montserrat in 1997; while extensive scorch zones were observed 1–3 km from the periphery of the PDC margin following the eruptions at both Mount St Helens in 1980 and Mt Lamington in 1951.

Jenkins et al. (2017) noted a few instances of fires caused by the lava flow following the Fogo eruption in 2014–2015. They highlighted that although minimal damage due to fire occurred in this eruption due to lava flows, this could have been greater if the urban area were made of more flammable construction (such as seen in Hawai'i) and fuel (such as gas canisters) had not been removed in a timely manner.

During the 2002 eruption of Nyiragongo volcano, between 60 and 100 people were killed owing to the explosion of a gas station surrounded by lava, and about 470 were injured with burns, fractures and/or gas intoxication (Tedesco et al., 2007; Balagizi et al., 2018).

Use of non-combustible construction materials and ensuring that buildings remain well sealed during volcanic eruptions are key control measures. This combined with preparedness in dealing with lava flows and securing energy supplies can reduce the impact of urban fires during/following volcanic eruptions.

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Coordinating agency or organisation:

School of Engineering, University of Edinburgh.

GH0020 / **GEOHAZARD / Volcanogenic**

Subsidence and Uplift, Including Shoreline Change (Magmatic/Volcanic Trigger)

Definition

Volcanic uplift and subsidence are deformations of the ground associated with volcanic unrest and eruptions (Dzurisin, 2007).

Reference

Dzurisin, D., 2007. Volcano Deformation. Springer.

Annotations

Synonyms

None.

Additional scientific description

Uplift and subsidence may occur before, during and after volcanic eruptions (Dzurisin, 2007). Before eruptions, uplift and/or subsidence may be among the first signs that a magmatic system is restless, so monitoring and understanding ground deformation is critical to attempts to understand magmatic systems, forecast eruptions and mitigate volcanic risk (Dzurisin, 2007; Acocella et al., 2015).

'Volcanic unrest' is defined as any deviation of ground deformation, seismicity, gas emission, and/or other geophysical and geochemical indicators from normal baselines, increasing the probability of eruption (Acocella, 2019). Volcanic unrest may typically last from hours to months but at some caldera volcanoes, unrest episodes may last for years to decades (Acocella et al., 2015). Some volcanoes that have not erupted for tens to hundreds of years may experience repeated episodes of unrest over several years before a critical threshold is reached and an eruption occurs (e.g., Sigmundsson et al., 2010).

During unrest at volcanoes, ground deformation is usually on the order of millimetres to centimetres per year and it is not uncommon for the centre of uplift to move (e.g., Di Vito et al., 2016). Some caldera volcanoes may show deformation rates of metres per year (e.g., Acocella, 2019) and some calderas show very long-term ground deformation ('resurgence') which may cause uplift of up to 1 km over hundreds to thousands of years (e.g., Galetto et al., 2017; Acocella, 2019).

Volcanic calderas are some of the most dangerous volcanoes on Earth and many have large populations living in and around the caldera (Acocella et al., 2015). They have surface depressions from ~1 km to tens of kilometres across, and up to several kilometres in topographic change from rim to floor (Acocella et al., 2015). Some contain lakes (e.g., Taal, Philippines) and some are semi-submarine (e.g., Santorini, Greece; Krakatau, Indonesia). Most calderas have large (over 1000 km3), long-lived, heterogeneous and active magmatic systems and about 20 caldera volcanoes show unrest each year, most driven by magma intrusion (Acocella et al., 2015).

For example, the Campi Flegrei caldera (Italy) is 12 km across and lies under the outskirts of Naples. At least 5 m of uplift was observed in the hours to days before the last eruption at Campi Flegrei in 1538 (from Monte Nuovo) resulting in the seaward retreat of the shoreline by '200 paces' (Parascandola, 1947; Dvorak and Gasparini, 1991). Campi Flegrei experienced major uplifts in 1950–1951, 1969–1972 and 1982–1984 which cumulatively raised the town of Pozzuoli by 4 m. Pozzuoli experienced a maximum of 1.8 m of uplift during unrest in 1982–1984 (Berrino et al., 1984).

Metrics and numeric limits

Not identified.

Key relevant UN convention/multilateral treaty

Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015).

Examples of drivers, outcomes and risk management

Uplift is typically associated with pressurisation ('inflation') of a shallow (few kilometres below the surface) magmatic system caused by the injection of magma but may also be caused by volatile degassing of a magma body (e.g., Lowenstern et al., 2006; Dzurisin, 2007; Sparks et al., 2012; Reath et al., 2020). Subsidence is associated with depressurisation ('deflation') of a magmatic system and may be caused by magma cooling and solidification, or the outflow of magma (during eruption or lateral migration into dykes or sills, e.g., Sigmundsson et al., 2015). Subsurface hydrothermal systems at volcanoes may also cause ground deformation (Gottsmann et al., 2006), as may tectonic events such as large earthquakes (Battaglia et al., 1999; Pritchard et al., 2019).

Near real-time ground deformation monitoring may enable scientists to anticipate the start of eruptions and key hazardous events during eruptions (e.g., Sparks et al., 2012; Sigmundsson et al., 2015; Fernández et al., 2017; Pallister et al., 2019). Satellite technologies such as InSAR have the potential to make a significant contribution to volcano ground deformation monitoring, especially in the form of regional surveys and for remote volcanoes with limited monitoring infrastructure (Ebmeier et al., 2018). Numerical simulations of 'inflation' and 'deflation' at volcanoes are generally carried out to understand and interpret observed ground deformation in terms of the dynamics and shape of the pressure source (e.g., Gottsmann et al., 2006).

Damage can be caused to buildings (Pingue et al., 2011), transport networks, critical infrastructure and facilities hampering response and mitigation efforts. Coastal regions affected by uplift/subsidence may be unable to use harbours and ferries for evacuation purposes (e.g., Alberico et al., 2012). Most damage during unrest at Campi Flegrei in 1982–1984 occurred within 2 km of the centre of uplift where total vertical movement exceeded about 60% of its maximum value of about 1.8 m but there was also intense volcanic earthquake activity (Barberi et al., 1984; Berrino et al., 1984; Charlton et al., 2020). Multiple hazards will occur before, during and after eruptions leading to cascading impacts, so risk mitigation measures need to account for this (e.g., Charlton et al., 2020).

Volcanic unrest associated with uplift and/or subsidence may cause significant distress to residents, with associated evacuations causing permanent displacement for some and loss of livelihoods (e.g., Barberi et al., 1984; Longo, 2019). A risk perception study at Campi Flegrei showed that residents who remembered the unrest episodes of the 1970s and 1980s were more concerned about unrest than an eruption (Ricci et al., 2013). Testing and practicing evacuation procedures for future response may enhance the awareness and preparedness of populations (e.g., Commune di Napoli, 2019).

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Coordinating agency or organisation

British Geological Survey (BGS).

GH0021 / **GEOHAZARDS / Other Geohazard**

Ground Shaking (induced earthquake, reservoir fill, dams, cavity collapse, underground explosion, impact, hydrocarbon fields, shale exploration, etc.)

Definition

Induced seismic ground shaking comprises non-tectonic (i.e., non-natural) earthquakes which result from human activities that alter the stresses and strains on the Earth's crust. Most induced seismicity is of a low magnitude and higher frequency than larger magnitude events with longer wavelengths and lower frequencies (USGS, 2016).

Reference

USGS, 2016. EarthWord – Induced Seismicity. United States Geological Survey (USGS). www.usgs.gov/news/earthword-%E2%80%93-induced-seismicity Accessed 21 October 2020.

Annotations

Synonyms

Seismicity, Shaking intensity, Ground motion, Ground vibration, Peak ground acceleration (PGA), Local ground response, Earth tremor, Vibration.

Additional scientific description

An earthquake is the sudden release of energy and ground shaking resulting from rocks breaking and moving along a fault line. Earthquake ground shaking is produced by seismic waves that travel through the Earth and along its surface. All earthquakes, both natural and man-made, generate seismic waves. Seismic waves radiate outward from the earthquake origin, forming a circular wave front that causes shaking over an extended region (Stein and Wysession, 2003). Ground shaking is a predominant seismic hazard, causing more than 90% of earthquake-related damage and loss (National Institute of Building Sciences Building Seismic Safety Council, 2010).

The strength and duration of the ground shaking at any location depends on many factors, predominantly the magnitude of the earthquake, the earthquake mechanism (i.e., the fault orientation and direction of slip), the distance to the earthquake origin, and local soil conditions (Kramer, 1996; USGS, no date a). Thus, ground shaking at each site from an earthquake is unique and can vary significantly from location to location. There are many human activities that can cause induced earthquakes including: wastewater disposal, mining, development of artificial lakes, extraction of fossil fuels, extraction of groundwater, development of geothermal energy, hydraulic fracturing, and subsurface storage of carbon dioxide.

Earthquake magnitudes are given using one of several broadly equivalent scales, with the 'moment magnitude' scaling being the preferred measure of an earthquake's size, as it quantifies the energy released by the earthquake (USGS, no date b). The magnitude scale is logarithmic; each increase of 1 magnitude unit (i.e., 4.3 to 5.3) represents an order of magnitude (factor of 10) increase in the amplitude of seismic measurements, and a factor of 32 increase in the energy release of an earthquake (USGS, no date b). Earthquakes of Magnitude 7.0 and above can be expected to cause widespread, intense ground shaking; earthquakes of Magnitudes 6.0 to 6.9 may cause local damage. Note that damage may be more severe and widespread for an earthquake of a given magnitude and other characteristics in regions of fragile buildings and high-density population (USGS, no date b).

Metrics and numeric limits

Although there is no globally agreed metric available, there is a global earthquake risk model (Silva et al., 2018) and there are several other Global Earthquake Model Foundation initiatives including a Global Exposure Database for Multi-Hazard Risk Analysis (GEM, no date). The Peak Ground Acceleration method (USGS, no date c; see below for explanation) for measuring ground shaking is the preferred approach, but global use is limited by the distribution of instrumentation.

There are many metrics for measuring ground shaking at a particular location:

- Qualitative intensity measures, like the Modified Mercalli intensity (MMI) scale (Wood and Neumann, 1931), and similar scales such as the Medvedev-Sponheuer-Kárník (MSK) scale or the European Macrointensity Scale (EMS-98) (Grünthal, 1998), describe the severity of an earthquake in terms of its effects on the Earth's surface, the infrastructure and the population (USGS, no date c). MMI values range from I (not felt) to XII (Total Damage), and the threshold for structural damage begins at VI, although this varies with the fragility of buildings in any given region. For some earthquake reporting agencies, MMI XI and XII are no longer assigned and MMI X is available but has not been applied in recent times. Since 1931, it has become clear that many of the phenomena described by Wood and Neumann (1931) were less related to ground shaking and more to other factors that would promote widespread destruction (Dewey et al., 1995).
- Quantitative measures are direct measures of ground shaking by seismic instruments. A widely used and preferred metric for the strength of ground shaking is Peak Ground Acceleration (PGA). PGA is calculated as the greatest increase in velocity recorded by a particular station during an earthquake (USGS, no date c), and typically given in units of g (the Earth's gravitational acceleration on its surface; 9.81 m/s2). It is an appropriate measure because the physical force exerted by the ground motions against any object on the surface is proportional to the peak acceleration. For engineering purposes, additional metrics such as spectral acceleration, which measures the forces experienced by structures at specified frequencies to which the structures may be particularly vulnerable. Generally, PGA values of <0.1 g are not expected to cause much damage, while values of between 0.2 g and 0.8 g may cause moderate damage; anything above this is expected to be very damaging (USGS, no date a). It is important to note that the amount of damage caused by ground motions of any given intensity in an area is highly dependent on the strength of infrastructure in that area. The greatest recorded ground motion to date was 4.3 g in the 2008 Iwate-Miyagi earthquake, Japan (Yamada et al., 2010).

Ground shaking can last from a few seconds in small, nearby earthquakes to several minutes in the largest earthquakes. HiQuake is a human induced earthquake database with more than 700 entries across the world for the period 1868 to 2016 (Foulger et al., 2018).

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

On 21 October 2020 the HiQuake database had 1196 recorded events (HiQuake database, no date). These were linked to activities in the following percentages: fracking 33%; mining 25%; water reservoir impoundment 16%; conventional oil and gas 11%; geothermal 6%; waste fluid disposal 4%; nuclear explosion 2%; research 1%; unspecified oil and gas / waste fluid disposal 1%; groundwater extraction 0.6%; deep penetrating bomb 0.3%; construction 0.2%; carbon capture and storage 0.2%; coal bed methane 0.1%; and chemical explosions 0.1%.

Seismic risk from ground shaking is best managed through accurate estimation of the likelihood of seismic ground shaking at damaging levels, the implementation of and conformance to appropriate building codes, and governmental and popular awareness and preparation for earthquakes. Monitoring can be used as a tool to manage anthropogenic activities that cause micro-seismicity, such as rates of fluid or gas discharge into or abstraction from the ground (USGS, no date d).

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Coordinating agency or organisation

British Geological Survey.

GH0022 / **GEOHAZARD / Other Geohazard**

Liquefaction (Groundwater Trigger)

Definition

Liquefaction is the term applied to the loss of strength experienced in loosely packed, saturated or close to saturated sediments at or near the ground surface in response to strong ground shaking, such as earthquakes, cyclic loading, and vibration from machinery, or due to the development of excess pore pressure resulting from a change in head or confining pressures. The loss of strength causes the soil to behave like a viscous fluid, sometimes referred to as 'running sand', until the excess pore pressure returns to hydrostatic (USGS, no date).

References

USGS, no date. Science Explorer: Liquefaction. United States Geological Survey (USGS). www.usgs.gov/science-explorer-results?es=liquefaction Accessed 12 October 2020.

Annotations

Synonyms

Quick sand, Running sand, Boiling sand.

Additional scientific description

Soil propensity to liquefaction has been related to grading, uniformity of grain size and relative density or voids ratio. A uniformly graded soil is more susceptible to soil liquefaction than a well-graded soil because the resistance to volumetric strain of a well-graded soil decreases the amount of excess pore pressure that can develop under undrained conditions. Historically, sands were considered to be the only type of soil susceptible to liquefaction. Yet, liquefaction also occurs in gravel and silt (Seed et al., 2003). 'Running sand' or 'boiling sand' is a product of the liquefaction process that can also occur in peat.

Liquefaction susceptibility is also influenced by particle shape; soil deposits with rounded particles being more susceptible to liquefaction than soils with angular particles. Structureless anthropogenic soils, such as those placed during land reclamation are susceptible to liquefaction. During construction, liquefaction occurs when the groundwater conditions reduce the effective stress of the soil to zero. At this point, the seepage pressure can disturb the soil structure and mobilise the sediment as quick, running or boiling sand (BRANZ Seismic Resilience, no date).

Liquefaction, as a secondary hazard associated with earthquakes, can also manifest via surface ruptures and fissures, as seen in Christchurch, New Zealand in 2011 (Cubrinovski, 2013).

The liquefaction associated with the Christchurch earthquakes caused significant disruption to transport infrastructure, and to storm- and wastewater networks, and posed physical and mental health hazards for the exposed community and clean-up (Villemure et al., 2012). From a human health perspective, the liquefaction material posed several hazards. Due to the extensive damage to the sewage disposal networks from lateral spreading and differential settlement, there was a risk that much of the liquefaction ejecta had been contaminated with raw sewage creating a long-term health risk to the population. During hot and windy conditions, the dry finer portions of silt were mobilised by the wind creating a possible respiratory health hazard. Many volunteers were involved in the clean-up operations. Indeed, the much-celebrated Student-Army was successfully used to coordinate the work around the city (Villemure et al., 2012).

Metrics and numeric limits

Areas that are most prone to earthquakes tend to undertake earthquake hazard susceptibility mapping, which usually embraces zones that are prone to liquefaction (USGS, no date). These commonly include more recently deposited lithologies such as Alluvium or Quaternary deposits.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

The consequences to structures and infrastructure of liquefaction include: differential settlement of structures often resulting in cracking; loss of bearing support; flotation of buried structures such as sewer lines, tanks, and pipes; strong lateral forces against retaining structures such as seawalls; lateral spreading (limited lateral movement); and lateral flows (extensive lateral movement), particularly impacting on slopes or valley sides (e.g., Cubrinovski, 2013).

The primary mitigation measure is to use planning to avoid development over liquefiable soils. Other types of mitigation are incorporated in building design (NZGS and MB IE, 2017). During construction, controlling both the rate of excavation and the head, or increasing seepage flow paths to reduce seepage forces are the key methods used to minimise liquefaction (Pane et al., 2015).

Health impacts are associated with primary consequences of liquefaction material both when wet and when material is dry and dusty; as well as secondary impacts from damage to infrastructure such as water and sewage pipes and health care facilities (Cubrinovski, 2013).

References

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Coordinating agency or organisation

British Geological Survey.

GH0023 / **GEOHAZARD / Other Geohazard**

Ground Fissuring

Definition

Ground fissures form in response to tensional stresses, most commonly in unconsolidated sediment, but also in rock (Arizona Geological Survey, 2020).

Reference

Arizona Geological Survey, 2020. Earth Fissures and Ground Subsidence. https://azgs.arizona.edu/center-natural-hazards/earth-fissures-ground-subsidence#:~:text=Earth%20Fissures%20are%20open%20ground,sinking%20of%20the%20Earth's%20surface Accessed 20 October 2020.

Annotations

Synonyms

Ground deformation, Subsidence, Surface faulting.

Additional scientific description

Natural or anthropogenic ground desiccation associated with subsidence can lead to ground fissuring. Ground fissures may also form as incipient indicators of coastal land sliding, ground spreading or cambering, for example, induced by mining or karst subsidence.

Ayalew et al. (2004) suggested that ground fissures in the Ethiopian rift valley may be related to aseismic tectonic strain, piping and hydraulic compaction.

Surface fissures are also associated with earthquakes.

The size and spatial extent of surface rupture, fissures and uplift/subsidence depends on the type and context. In Arizona, fissures range from discontinuous hairline fractures to open ground cracks that exceed 3 km in length, are up to 7 m wide, and tens of metres deep. In this context, fissure depth is likely to reflect the depth to the groundwater (Arizona Geological Survey, 2020).

Metrics and numeric limits

Not identified.

Key relevant UN convention / multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Ground fissures can cause loss of agricultural land, and damage to buildings, roads, canals and utility infrastructure (e.g., gas, oil and water lines). In addition to the immediate, local risk posed by collapsing infrastructure, this damage may hamper rescue and rebuilding efforts by impeding transportation and utility delivery. In the worst cases, damage to lifelines may cause local flooding (e.g., water lines), environmental impacts (e.g., contamination) and fires (gas lines) (Arizona Geological Survey, 2020).

The potential also exists for disruption due to flooding or re-routing of rivers if the river channel has been sufficiently modified (Holbrook and Schumm, 1999).

Livestock and wildlife injury or death have been reported as well as impacts on humans (Arizona Geological Survey, 2020).

Ground subsidence and resulting earth fissures affect more than 3000 square miles in Arizona, including expanding areas of Phoenix and Tucson (Arizona Geological Survey, 2020). The cost to the Arizona economy is not known, but probably reaches the millions of dollars annually. Repairs to an irrigation canal near Scottsdale Airpark in 2007 were estimated at USD 820,000, and that is just a single incident involving one canal. During construction of the Red Mountain Highway in Phoenix, the cost of mitigating an earth fissure that impinged on the road bed was USD 200,000 (Arizona Geological Survey, 2020).

Suggested remedial measures include reducing the dependence on groundwater by using alternative sources; planning to avoid fissures when constructing infrastructure or buildings; manage drainage to avoid losses into fissures and monitor water infrastructure for flow reversal (Arizona Geological Survey, 2020).

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Coordinating agency or organisation

British Geological Survey.

GH0024 / **GEOHAZARD / Other Geohazard**

Subsidence and Uplift Including Shoreline Change

Definition

Subsidence is a lowering or collapse of the ground (BGS, 2020). Uplift is the converse.

References

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Annotations

Synonyms

Uplift, Subsidence, Ground deformation, Surface faulting, Coseismic subsidence.

Additional scientific description

Subsidence and uplift are caused by many factors, including the impacts of mining or tunnelling, consolidation, sinkholes, or of groundwater and moisture changes on expansive soils (BGS, 2020). Such near-surface, relatively shallow crustal, or human-generated processes, are often localised. Several crustal scale processes also drive subsidence and uplift that tend to be more regional in scale. Crustal movements occur in response to several different mechanisms, including tectonic, glacio-isostatic (Milne et al., 2006), erosional isostatic (denudation; Watts, 2001) and hydro-isostatic (Watts, 2001) processes. These operate over different timescales and different wavelengths. Crustal movements, climate change-driven sea-level rise and erosion-derived sedimentation can result in shoreline change. Tectonic uplift and subsidence are the distributed vertical permanent ground deformations (warping) that result from displacement on a dipping (inclined) fault (Styron, 2019). Earthquake surface ruptures and fissures are localised ground displacements that develop during and immediately after an earthquake, where the fault which hosted the earthquake intersects the Earth's surface. Surface ruptures represent the upward continuation of fault slip at depth, while fissures are smaller displacements, or more distributed deformation in and around the rupture area (PNSN, no date). Volcanic uplift and subsidence are deformations of the ground associated with volcanic unrest and eruptions (Dzurisin, 2007). Hydro-isostatic and erosional-isostatic deformation occur in response to the stress changes induced by changing ground water levels and load (erosion). Hydro-isostatic movements are largely anthropogenic or climatic and therefore commonly seasonal.

Ground-level rise is commonly associated with plate subduction zones, such as the Himalayas where the Eurasian and Indian plates converge (USGS, 2015). Uplift can also be driven by swelling, or mantle plumes, such as the Iceland Plume form in higher temperature regions of the Earth's mantle. Subsidence may be associated with plates moving apart, for example in rift valleys such as the Ethiopian rift valley. The relative motion of the crust on either side of faulting associated with earthquakes results in persistent or permanent deformation of the Earth's surface. Surface ruptures, fissures, and uplift and subsidence are all manifestations of this longer-term deformation, and although less dramatic, may all pose hazards during and after earthquakes. Lithospheric flexure also responds to extensional and compressional tectonic forces, including movement associated with the formation of rift valleys (commonly associated with plate boundaries) and mountain belts as well as strike slip faults and fault zones (Watts, 2001).

In the coastal environment, as well as the potential tectonic impacts, sediment and global sea-level rise impact on shore-line change. Sediment loading can exacerbate regional subsidence, thereby increasing the relative sea-level rise. In coastal areas where accelerated glacial wasting has been reported, glacio-isostatic rebound results in a relative rise in ground level, as exemplified in the wasting of the Laurentide Ice Sheet (Simon et al., 2016).

Local-to-regional scale subsidence and uplift resulting from changes in groundwater or porewater pressures occur in areas that are underlain by compressible and elastically deforming soils responding to groundwater withdrawal. Cohesive soils commonly exhibit seasonal changes in moisture content that can be associated with local subsidence (e.g., Simic et al., 2015).

Anthropogenic impacts on ground level, primarily result from dewatering for potable supply or for subsurface mining or engineering (Cigna et al., 2017).

Metrics and numeric limits

Rates of uplift in the Himalayas are reported to be in the order of 1 cm/yr (USGS, 2015). Global sea-level rise is in the order of 1.8 mm/yr, but relative sea-level rise varies considerably in accordance with other processes such as sedimentation or subsidence (USGS, no date a). High rates of uplift in Iceland (25–29 mm/yr) have been related to glacial isostatic adjustment with a feedback on plume evolution as a consequence of reduced pressure increasing magma production rates (Schmidt et al., 2013).

The size and spatial extent of surface rupture, fissures and uplift/subsidence associated with earthquakes depends on the type, magnitude and depth of the earthquake as well as the distance from the earthquake (Biasi et al., 2006; USGS, no date b).

Tectonic uplift and subsidence are generally as large or larger than the displacement of the surface rupture; moderate to large earthquakes in the crust that do not rupture to the surface will still broadly warp the region. The magnitude of the displacement will decrease with increasing distance from the earthquake, but in the case of ruptures on inclined faults such as subduction zones (rather than vertical strike-slip faults) uplift or subsidence of at least 1 m may extend for more than 200 km from the fault trace for the largest earthquakes (Styron, 2019). Both effects will extend along the length of the earthquake fault, a distance of a few kilometres for Magnitude 6 earthquakes to more than 1000 km for Magnitude 9 earthquakes.

Ground-level response to groundwater dewatering is a global issue (USGS, no date c). Values of up to 53 mm/yr have been determined using InSAR monitoring of Kabul (Meldebekova, 2020).

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Surface ruptures and fissures can cause damage to buildings, roads, and utility infrastructure (e.g., gas and water lines). In addition to the immediate, local risk posed by collapsing infrastructure, this damage may hamper rescue and rebuilding efforts by impeding transportation and utility delivery. In the worst cases, damage to lifelines may cause local flooding (e.g., water lines), environmental impacts (e.g., oil pipelines) and even highly destructive fires (gas lines) that may be more damaging than the initial earthquake. Potential also exists for disruption due to flooding or re-routing of rivers if the river channel has been sufficiently modified (Holbrook and Schumm, 1999).

Shoreline change poses a threat to coastal settlements, businesses and tourism. There is also potential for impacts on coastal stability and groundwater resources, such as saline intrusion (USGS, no date d). Potential impacts are especially significant for atoll islands with shallow unsaturated zones. These islands are particularly susceptible to impacts on groundwater resources and populations (UNESCO, 2019).

While no technology exists for reducing these or other earthquake hazards, the risk to infrastructure posed by surface rupture and fissures can be mitigated to some degree by not building on known fault traces, seismic retrofitting of existing buildings, and engineering of pipelines with enough flexibility to absorb the displacement by bending and flexing, rather than breaking (e.g., USGS, 2003).

Coastal change can impact harbour water depth and damage infrastructure. In these zones, modelling to enable adaptive planning is the best form of mitigation (Steven et al., 2020).

In areas where stopping anthropogenic groundwater dewatering leads to rising ground levels, as well as potential impacts on infrastructure, consideration should be given to impacts on water quality, such as where mine water rebound results in the mixing of mining and potable water (Boak et al., 2007).

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Coordinating agency or organisation

British Geological Survey.

GH0025 / **GEOHAZARD / Other Geohazard**

Shrink-Swell Subsidence

Definition

Subsidence is a lowering or collapse of the ground, caused by various factors, including groundwater lowering, sub-surface mining or tunnelling, consolidation, sinkholes, or changes in moisture content in expansive soils. Shrink-swell is the term applied to the behaviour of expansive soils, which are a group of soils that exhibit volumetric change in response to changes in moisture content, such that they shrink in response to desiccation and swell by hydration, resulting in ground subsidence and ground heave respectively (BGS, 2020).

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Annotations

Synonyms

Problem soils, Expansive clay subsidence, Clay shrink-swell, Pipe clays (American term).

Additional scientific description

The properties of expansive soils are attributable to the presence of swelling clay minerals. These clays range in their potential to absorb water according to their different structures. Expansive clay groups with increasing susceptibility to swelling include kandites (e.g., kaolinite, haloysite), illites (e.g., phengite, glauconite), vermiculites and smectites (e.g., montmorillonite, talc). These minerals are a product of weathering, commonly formed on land and then transported to the oceans. Their distribution reflects the underlying source rock geology, its diagenesis and stress history (e.g., stress-induced smectite to illite transformations) and the nature of the weathering, for example, wet climates are associated with kaolinite rich soils and dry environments are characterised by smectite clays (Eberl, 1984).

Metrics and numeric limits

For the most expansive clays, expansions of 10% are common (Nelson and Miller, 1992). In the field, expansive clay soils are recognisable in the dry season by the deep cracks that form in roughly polygonal patterns. The zone of seasonal moisture content fluctuation can extend from one to tens of metres in depth. This creates cyclic shrink/swell behaviour in the upper part of the soil column, and cracks can extend to considerable depths.

Key relevant UN convention / multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Beneath the depth of influence of atmospheric change in moisture content, the water demand of vegetation, particularly trees on clay soils dominates the moisture content changes that lead to the soils shrinking (subsidence) and swelling (heave). Where subsidence and heave occur beneath or close to properties and infrastructure this can result in damage (Florida Department of Environmental Protection, 2020). The most obvious way in which expansive soils can damage foundations is by uplift as they swell with moisture increases. Swelling soils lift up and crack lightly-loaded, continuous strip footings, and frequently cause distress in floor slabs. Uplift is commonly differential, reflecting the different resisting forces across the structural foundations.

The extensive distribution of these soils across the world has necessitated characterisation through index testing to inform remedial measures. At its simplest, the plasticity indices are utilised to define inorganic clays with inherent swelling capacity (e.g., BRE, 1993). Expansion of soils can also be measured in the laboratory directly, by immersing a remolded soil sample and measuring its volume change or using LiDAR techniques (Hobbs et al., 2014).

The best way to avoid damage from expansive soils is to extend building foundations beneath the zone of water content fluctuation as modified to reflect the presence of vegetation (Rogers et al., no date).

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Coordinating agency or organisation

British Geological Society.

Sinkhole

Definition

A sinkhole is a closed depression in karst (a landscape resulting from the dissolution of soluble rock) by current or palaeo internal drainage, also known as a doline. This is one of several hazards that result in subsidence, i.e., lowering or collapse of the ground (adapted from USGS, no date; and BGS, no date).

References

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Annotations

Synonyms

Doline cenote, Sink, Sink-hole, Swallet, Swallow.

Additional scientific description

Dolines (sinkholes) are part of the hydrological system that shapes karst landscapes and can be considered in terms of fluid recharge, through-flow and discharge (e.g., springs and discharge points). Their rates of formation reflect the lithological and hydrological conditions (head and discharge). For example, of the soluble rocks and given a comparable hydrogeological setting, the rate of dissolution of salt > gypsum > Mesozoic limestone > Palaeozoic limestone (Waltham et al., 2004). There is an increasing awareness that dissolution may result from both meteoric recharge and groundwater or hypogene fluid flow (water or other fluids and gases) (Dublyansky, 2014).

Groundwater chemistry is also important in influencing the rate and distribution of sinkholes. For example, while limestone is only very weakly soluble in water of neutral pH, its solubility increases in acidic conditions, such as due to the input of carbon dioxide from biological transpiration or due to the oxidation of pyrite. Commonly, the mixing of water from different flow paths results in increased dissolution potential.

Sinkholes are classified in accordance with the mode of formation, including but not limited to the following (e.g., Waltham et al., 2004): a dissolution sinkhole is formed by dissolutional lowering of the exposed soluble rock surface in and around zones of water recharge to soluble rock; a subsidence sinkhole results from recharge water mobilisation of sediment into underlying cavernous rock; a suffosion sinkhole is formed due to recharge water mobilisation of sediment through unconsolidated sediment cover over karst; a collapse sinkhole results from the collapse of insoluble capping rock into underlying cavernous rock; a buried sinkhole is sediment filled; while a drop out sinkhole is formed rapidly due to soil cover collapse.

The triggering of sinkholes can also be the result of either surface or subsurface changes in load or groundwater conditions.

Other types of karst hollow (EPA, 2002) with internal drainage include karst geomorphological features referred to as uvala (a closed depression with multiple recharge points), polje (a closed depression with a wide flat-floored and long axis developed parallel to major structural trends), and cockpit (a star-shaped depression with a concave floor and surrounded by steep convex hill slopes).

The manifestation of collapse subsidence associated with mining can be comparable to that of sinkholes. Sinkholes can also occur in specific non-soluble rock settings such as lava tubes or pseudokarst.

Although a natural process, the formation of sinkholes is often accelerated or triggered by human action.

Many new sinkholes have been correlated to land-use practices, especially from groundwater pumping and construction and development practices. Sinkholes can also form when natural water-drainage patterns are changed, and new water-diversion systems are developed. Some sinkholes form when the land surface is changed, such as when industrial and runoff-storage ponds are created. The substantial weight of the new material can trigger an underground collapse of supporting material, causing a sinkhole (USGS, no date).

The overburden sediments that cover buried cavities in some aquifer systems are delicately balanced by groundwater fluid pressure, whereby the water below ground is actually helping to keep the surface soil in place. Groundwater pumping for urban water supply and for irrigation can produce new sinkholes in sinkhole-prone areas. If pumping results in a lowering of groundwater levels, then underground structural failure, and thus, sinkholes, can occur (USGS, no date).

Broken land drains, water mains and sewerage pipes, increased rainfall, storm events, modified drainage and diverted surface water can all help wash sediment into the underlying limestone, causing subsidence. There have been many well documented occurrences of sinkholes forming beneath broken water mains, unlined storm-water culverts and leaking swimming pools (BGS, 2017).

Metrics and numeric limits

The size and density of sinkholes reflects the distribution of recharge or flow paths, for example, surface karst with numerous small recharge points (diffuse flow) over heavily fractured, more permeable rock, or fewer large recharge points in lower permeability strata. Similarly, where groundwater flow dominates, sinkhole formation processes are focused on structural and lithological boundaries. The size of sinkholes ranges from a few centimetres to hundreds of metres in diameter, and depths of decametres to a hundred metres or more.

Key relevant UN convention / multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

The surface expression of sinkholes can be triggered by rainfall, changing groundwater levels (natural and anthropogenic), inundation (e.g., flooding or pipe leakage), loading (e.g., flooding or construction), erosion, and weathering and ground vibration. Sinkholes may also be triggered by sub-surface activity such as mining or tunnelling. In many landscapes, sinkholes form imperceptibly slowly (USGS, no date; BGS, 2017).

However, if collapse subsidence occurs, they can express themselves rapidly. This is particularly significant in urban landscapes where the surface rupture can damage buildings and infrastructure, occasionally associated with loss of life (Waltham et al., 2004).

The best form of control is avoidance through planning: various remote sensing, geophysical and intrusive ground investigation techniques can be applied to locating sinkholes to enable the design of construction methods, for example, transferring load to more competent strata with piles, or the incorporation of span distances for rafts or geotextiles (Waltham et al., 2004).

Some construction techniques focus on void filling, for example, types of grouting are used to prevent or remediate sinkholes (Waltham et al., 2004).

Any remediation solution should fully consider the hydrological and hydrogeological context.

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Coordinating agency or organisation

British Geological Survey.

GH0027 / **GEOHAZARD / Other Geohazard**

Ground Gases (CH4, Rn, etc.)

Definition

Ground gases that result from material decay (natural or anthropogenic) typically include radon, methane, carbon dioxide, hydrogen sulphide, but may also include the break down products of other compounds, such as nitrogen, alcohols, alkanes, cycloalkanes and alkenes, aromatic hydrocarbons (monocyclic or polycyclic); esters and ethers, as well as halogenated compounds and organosulphur. Ground gases derived from magma (molten or semi-molten natural material derived from the melting of land or oceanic crust) include carbon dioxide, sulphur dioxide, hydrogen sulphide and hydrogen halides. Ground gases are gases released in combination with water vapour and particulate matter during volcanogenic events, or via fumaroles, and hydrothermal systems (adapted from NHBC (UK), 2007; IVHHN, 2020; US EPA, no date; and USGS, no date).

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Annotations

Synonyms

Volcanic gases, Magmatic gases, Landfill gas, Gas-contaminated land.

Additional scientific description

Volcanogenic gases escape from magma as a consequence of the pressure relief that occurs as the magma rises to the surface. These gases are also released via geothermal systems.

Chemical or biological processes generate ground gases, for example, the breakdown of uranium-bearing minerals releasing radon from granite or by oxidation and or biogenic reduction (releasing hydrogen sulphide). In addition, naturally occurring ground gases are generated by the biogenic decay of organic matter, for example methane, carbon dioxide and phosphine gas.

Landfill gas is a product of the largely biogenic decomposition of anthropogenic waste. Its composition reflects that of the waste, but is dominated by methane and carbon dioxide, becoming more carbon dioxide rich as the waste ages, and with a small amount of non-methane organic compounds. Methane is a potent greenhouse gas (US EPA, no date).

Ground gases comprise a hazard because of the risk to human health and or their flammability. As an example, the UK limits for the following gases are summarised below from sources other than earthquake triggered gases:

- Methane is a colourless, odourless flammable gas. When the concentration of methane in air (oxygen 20.9% by volume [% v/v]) is between the limits of 5% v/v and 15% v/v, an explosive mixture is formed. The Lower Explosive Limit (LEL) of methane is 5% v/v, which is equivalent to 100% LEL. The 15% v/v limit is known as the Upper Explosive Limit (UEL), but concentrations above this level cannot be assumed to represent safe concentrations, because of the potential for dilution to the UEL (NHBC, 2007).
- Carbon dioxide is a colourless, odourless gas, which, although non-flammable, is both a toxic gas and an asphyxiant. As carbon dioxide is denser than air, it will collect in low points and depressions, which can be an extreme hazard during foundation construction and earth movements on development sites. The Long-Term Exposure Limit (LTEL, 8-hour period) and the Short-Term Exposure Limit (STEL, 15-minute period), are 0.5% v/v and 1.5% v/v carbon dioxide, respectively (HSE, no date).
- Radon is a colourless, odourless radioactive gas derived from the radioactive decay of radium, itself from radioactive decay of uranium. The UK target level for homes is 100 Bq m3 (PHE, no date).
- Levels of hydrogen sulphide of 100 ppm and higher are considered immediately dangerous to life and health (NHBC, 2007).

Another source of ground gas associated with continental margins is methane hydrates (Geology.com, 2005-2020). Similarly, ground gases and vapours are emitted from volcanogenic sources.

Metrics and numeric limits

No globally agreed limits for ground gases (earthquake trigger).

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

Ground gases are a hazard in terms of risk to human health, flammability and climate change (greenhouse gases). For these reasons, where possible, ground gas is monitored and controlled. Where buildings may come into contact with ground gases, specialist construction techniques are deployed to protect human health (e.g., NHBC, 2007). In the case of earthquake-triggered gases, consideration should also be given to the associated particulate matter.

Landfill gas management has been a focal point for national scale reductions in carbon dioxide emissions. For example, in 2018 waste management-related carbon dioxide formed 4.6% of UK carbon dioxide emissions (BEIS, 2020).

Ground gases occur in mining environments, for example in mining for coal (carbon dioxide, methane), potash (methane, nitrogen) and shale gas (BGS, no date). In the UK, in these environments, control measures are guided by the Health and Safety Executive.

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Coordinating agency or organisation

British Geological Survey.

GH0028 / **GEOHAZARD / Other Geohazard**

Riverbank Erosion

Definition

Riverbank erosion is the removal of material from the banks of rivers when flowing water forces exceed bank resisting forces by the soil and vegetation, for example, when river levels are sufficiently high, primarily due to fluvial energy and atmospheric processes and secondarily because of the resultant geotechnical instability and consequential riverbank failure. Riverbank failure can also occur as a consequence of Earth hazards, such as volcanos and earthquakes (USDA, no date).

Reference

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Annotations

Synonyms

Stream bank deterioration, Stream bank disintegration.

Additional scientific description

Riverbank erosion primarily comprises corrasion (abrasion) and mass wasting. River energy, the primary driver for erosion, differs between, along and seasonally within river systems. The speed at which failed sediment masses are mobilised as fluvial sediment load affects the rate of exposure of the riverbank to further erosion. Consequently, riverbank erosion is a discontinuous process, strongly associated with higher energy events such as flooding (Das et al., 2014).

Background weathering that facilitates erosion includes processes that are subject to seasonality, and include flooding, precipitation, crack formation, cryogenic processes, poaching and anthropogenic changes to the natural geomorphology (Darby et al., 2007).

Bhuiyan et al. (2017) reported that the rivers of Bangladesh are responsible for cumulative annual erosion of up to 10,000 hectares of land. They pointed out that as well as floodplains and settlements, Bangladesh also loses several kilometres of roads, railways, and flood control embankments each year. They stated that no other issues are as disastrous as riverbank erosion with regard to long-term effects on people and society in Bangladesh (Bhuiyan et al., 2017).

Metrics and numeric limits

Riverbank erosion results in significant land loss. Hooke (1980) presented the results from published data that demonstrate a relationship between erosion rates (m/yr) and catchment area (km2), with annual erosion rates ranging from 0.5 m to 1000 m for drainage areas of 4 to 1000,000 km2 respectively.

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

While riverbank erosion is accelerated by flood events, because of both the hydraulic conditions and the sediment load that increases the erosional power of a given stream; antecedent conditions contribute to conditioning of the riverbank (Darby et al., 2007). In addition to the loss of land and infrastructure, the consequences of stream erosion and riverbank mass wasting are increased suspended sediment loads in streams, which impacts on water quality with consequential implications for human and ecological health (Grove et al., 2015).

Stream erosion is also associated with river scour, whereby bed sediment is eroded and may be redistributed. River scour is commonly focused on changes in bedform, which may be natural or artificial. For example, the impacts of scour on bridge foundations and other engineered infrastructure are well documented (Ozaukee County, no date).

Riverbank vegetation, for example mangroves, contributes to riverbank resilience to erosion, as do alluvial sediments. Mitigation of the impacts of bank erosion include planning and avoidance, and soft and engineered protection or renaturing. Some examples are presented by the Scottish Environment Protection Agency (SEPA, 2020).

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Coordinating agency or organisation

British Geological Survey.

GH0029 / **GEOHAZARD / Other Geohazard**

Sand Encroachment

Definition

Sand encroachment occurs generally in arid to semi-arid regions when grains of sand are carried by winds and form sandy accumulation on coasts, along water courses and on cultivated or uncultivated land. As the accumulations of sand (dunes) move, they bury towns, roads, oases, crops, market gardens, irrigation channels and dams, thus causing major material and socioeconomic damage (FAO, 2010).

Reference

FAO, 2010. Fighting sand encroachment. Lessons from Mauritania. Food and Agriculture Organization of the United Nations (FAO). www.fao.org/3/a-i1488e.pdf Accessed 26 November 2019.

Annotations

Synonyms

Not applicable.

Additional scientific description

Different factors and processes foster the formation and movement of sand masses, such as violent wind blowing over large areas, sparse or stunted vegetation, and degraded soil that is mobile, dry or bare (Khalaf and Al-ajmi, 1993; FAO, 2010).

Sand particles in movement are the site of various interactions, the main ones being:

- Avalanche effect - the avalanche effect is the result of saltation. As the grains of sand fall back, they cause the displacement of a larger quantity of particles, so that the more intense the saltation process caused by the wind, the greater the number of particles set in motion, until a maximum or saturation point is reached, where the quantity lost is equal to the quantity gained at any given moment. The distance needed to reach the saturation point depends on the sensitivity of a soil to erosion: on a very fragile soil, it can occur over a distance of about 50 m, but requires more than 1000 m on a very cohesive soil (FAO, 2010).
- Sorting - the sorting mechanism concerns the wind's displacement of the finest and lightest particles, leaving behind the larger particles. This process gradually impoverishes the soil, since the organic matter made up of small light elements is the first to be removed (FAO, 2010).
- Corrosion - corrosion is the mechanical attack on the surface as the sand-laden wind blows over it. In arid regions, it is the aggravating cause of soil erosion and is seen in parallel streaks or the polishing of rocks (FAO, 2010).

When the wind grows lighter, it loses its capacity to carry sand particles, which are then dropped (FAO, 2010).

Forms of sandy accumulation vary widely, depending on landform, the nature of the soil on which they encroach, the presence or lack of vegetation, and the size of the grains of sand (Hamdan et al., 2016).

Metrics and numeric limits

The scale of the event varies depending on the wind speed, which is an essential factor, for it determines the force of sand removal; the greater the speed, the greater the carrying capacity. The second factor is the size and density of sand particles. Sandy encroachments can vary from 50 cm in height, 150 cm in length and 40 cm in breadth, to 20 to 40 km long and 50 to 200 m wide (Al-Helal and Al-Awadhi, 2006). Sand encroachment reporting should indicate the accumulation location, scale, sand sources, and transport zones.

Key relevant UN convention / multilateral treaty

Not applicable.

Examples of drivers, outcomes and risk management

All types of sand encroachment, no matter the size or duration, can create hazardous conditions affecting especially soil, vegetation, villages, roads (Boulghobra et al., 2015), railways and irrigation channels:

- The wind first carries off the finer parts of the soil, thus weakening the soil structure. As the soil becomes sandier, it is more vulnerable to the wind and has a reduced water retention capacity. Its colour turns from grey to white and then to red as it is scoured. The terrain is gradually broken up by the creation of small mounds surrounding the woody and grassy vegetation as this degrades. The land gradually becomes unsuitable for cultivation (FAO, 2010).
- The wind has both mechanical and physiological effects on vegetation:
  - Mechanical effects. The soil particles that are carried off collide with stalks and leaves with a force that abrades their tissue. In the zones from which the particles are carried off, roots are uncovered, and the vegetation risks being uprooted, while in zones where the particles are deposited the vegetation is steadily buried (FAO, 2010).
  - Physiological effects. The wind increases evaporation and dries out plants, mainly in the Kuwait dry season. The air's evaporating power is proportional to the square root of the wind speed. Moreover, the soil's water retention capacity is reduced, leading to water stress. The surrounding or moving mass of dry air tends to absorb humidity and exacerbate water deficit and this deficit is the main factor determining local vegetation, inasmuch as the latter has to adapt to the severe shortage of water (Khalaf and Al-ajmi, 1993).

References

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Coordinating agency or organisation

Food and Agriculture Organization of the United Nations.

GH0030 / **GEOHAZARD / Other Geohazard**

Aquifer Recharge (Systems Failure/ Outages)

Definition

An aquifer is a water-bearing rock that readily transmits water to wells and springs. It can be recharged either naturally (precipitation including rainfall or snow) or artificially (e.g., pumped river recharge via wells). Failure or outage can be due to derogation, well failure or contamination (USGS, no date).

Reference

USGS, no date. Aquifers and Groundwater. United States Geological Survey (USGS). www.usgs.gov/special-topic/water-science-school/science/aquifers-and-groundwater?qt-science_center_objects=0#qt-science_center_objects Accessed 20 October 2020.

Annotations

Synonyms

Groundwater recharge.

Additional scientific description

Groundwater is a finite but renewable resource. The amount of available groundwater is limited by the porosity and permeability of the aquifer, but it can be renewed by meteoric water or artificial recharge. Aquifers may be unconfined or confined. While the water table in an unconfined aquifer will be in hydraulic continuity with adjacent water courses, a confined aquifer may be isolated from adjacent watercourses by a capping of lower permeability strata. Consequently, meteoric recharge to unconfined aquifers is more direct and generally, depending on the thickness of the unsaturated zone, more rapid than to confined aquifers. Groundwater abstraction via water wells causes a reduction in the water table that is referred to as a cone of depression. Cones of depression are rarely truly cone shaped; the shape being influenced by aquifer permeability, which is rarely isotropic. If groundwater abstraction exceeds recharge, over-abstraction will result in aquifer depletion and potentially outages of supply. Outages can also result from damage to the abstraction well. This could be due to physical damage, for example, pipe fracture or physical blocking by a trapped object, such as a jammed pump. Alternatively, it might occur because of clogging of the permeable part of the well, most likely due to a form of geochemical precipitation. Derogation of supply can also be caused by abstraction from neighbouring parts of an aquifer, either for potable supply or dewatering for mineral extraction or construction. Physical changes to an aquifer and its permeability can be brought about by earthquake activity. More commonly, groundwater infrastructure may be prone to rupture or damage by ground shaking induced by earthquake or volcanic activity (US EPA, 2020).

Groundwater contamination can result from surface or sub-surface contaminants resulting from poor waste management, industry, mining and agriculture. Aquifer vulnerability to contamination reflects the extent of lower permeability materials that cover/ protect the aquifer. Potential contaminants include a very wide range of natural (volcanic) or anthropogenic chemical contaminants, as well as biological contaminants, such as Cryptosporidium (a microscopic parasite; Morris and Foster, 2000) and saline intrusion (USGS, no date).

Metrics and numeric limits

There is no internationally recognised definition of a groundwater aquifer or methods for assessing failure. An example of a metric is the Groundwater Directive 2006/118/EC to meet Article 17 of the European Water Framework (2000) (European Commission Environment, 2020). This states that, the definition of a groundwater body is its capacity to supply 10 m3 of water per day as an average or 50 persons or to support the ecological quality of a surface water body or groundwater dependent terrestrial ecosystem (UKTAG, 2011). Giordano (2009) reported that global groundwater extraction is in excess of 650 km3 per year, with India, the United States, China, Pakistan, Iran, Mexico, and Saudi Arabia collectively accounting for 75% of this total amount.

Key relevant UN convention/multilateral treaty

While there is no multilateral treaty, there are in the order of 200 transboundary aquifers and more than 3600 agreements and treaties pertaining to transboundary water (UNDESA, 2014).

Examples of drivers, outcomes and risk management

According to Fienen and Arshad (2016) issues include seawater intrusion and groundwater depletion.

- Seawater intrusion has particularly affected groundwater quality in major coastal irrigation regions such as Queensland in Australia, Florida in the United States, the southern Atlantic coastline of Spain, and Lebanon.
- Groundwater depletion has been particularly experienced in southern and central parts of Asia, northern China, the Middle East and North Africa, North America, parts of Australia, and many localised areas in southern Europe.

Groundwater protection requires effective planning and monitoring for resource management with regular reviews and provision for additional resources to meet increasing demand to meet growing demands in the context of population growth, urbanisation and climate change (Bricker et al., 2017). Planning is more effective when supported by groundwater resource mapping (e.g., MacDonald et al., 2012). For zones that are prone to earthquakes, effective planning is required to avoid zones of high susceptibility, or mitigation through engineering, construction material selection and possibly ground improvement (US EPA, 2018).

Some countries, such as the UK define source protection zones that show the risk of contamination from any activities that might cause pollution in the area (Environment Agency, 2018).

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Coordinating agency or organisation

British Geological Survey.

GH0031 / **GEOHAZARD / Other Geohazard**

Submarine Landslide

Definition

A submarine landslide is a downslope movement of sediment or rock under the effect of gravity, which occurs when the stresses acting downslope exceed the available strength of the sediment on the slope (Lee et al., 2007).

Reference

Lee, H.J., J. Locat, P. Desgagnés, J,.D. Parsons, B.G. McAdoo, D.L. Orange, P. Puig, F. Wong, P. Dartnell and E. Boulanger, 2007. Submarine mass movements on continental margins. In: Continental Margin Sedimentation. pp. 213-274. Wiley.

Annotations

Synonyms

Mass movement, Slump, Mudflow, Debris flow, Liquefaction flow, Turbidity current.

Additional scientific description

Submarine landslides occur preferentially in particular environments, including fjords, active river deltas, submarine canyons, volcanic islands and the open continental slope. Evaluating the relative stability of different types of seabed sediment requires an understanding of driving stresses and sediment strength. Stresses can be caused by gravity, earthquakes and storm waves. Resisting strength can be reduced by pore water and gas pressures, groundwater seepage, rapid sediment deposition, cyclic loading and human activity. Once slopes have become unstable or have failed, sediment strength may continue to decrease so, following slope failure, the failed mass moves downslope under the influence of gravity and possibly other forces. If the moving sediment is a viscous fluid, this is termed a mass flow (gravity flow). If the movements are essentially rigid, internally undeformed masses along discrete slip planes, they are termed slides. If the movement is formed of 'blocks' of failed material which rotate along curved slip, they are termed slumps. Another kind of landslide involves movement on a planar surface and is termed a translational slide. In each type, movement can be fast or slow. Extremely slow movement is called creep. Submarine slides can become mass flows (gravity flows) as the failed mass progressively disintegrates and continuous downslope movement occurs. End members of disintegrating slides have different terms. Debris flows are where the sediment is heterogeneous and may include larger clasts supported by a matrix of fine sediment. Mud flows are predominantly muddy sediment. Turbidity currents involve the downslope transport of a relatively dilute suspension of sediment grains that are supported by an upward component of fluid turbulence. Recent submarine landslide research has: (i) shown that landslides and sediment waves may generate similar deposits, which require careful interpretation; (ii) expanded knowledge of how strength develops in marine sediment; (iii) improved techniques for predicting sediment rheology; and (iv) developed methodologies for mapping and predicting the medium- to large-scale regional occurrence of submarine landslides. Based on the identification of the different submarine sediment failures identified above and the classification of subaerial landslides (Varnes, 1958; Hungr, 2014), submarine landslides may be classified as mass sediment movements termed slides (translational and rotational slumps) and mass flows (mudflow, debris flow, liquefaction and turbidity current).

Almost all submarine landslides have multiple causes, which differ significantly to their subaerial counterparts, for example, seabed slope is not that important as shown by the largest volume submarine landslides being located on the shallowest slopes. Submarine landslides are triggered either by an increase in the driving stresses, a decrease in sediment strength, or a combination of the two. The following triggers show the interplay of these factors, but their relative importance is not well understood. For example, in some environments one of these triggers will dominate, whereas in others a different trigger will be most significant. The main triggers identified for submarine landslides are erosion (undercutting the landslide foot), a rapid rate of sedimentation and earthquakes. Erosion is common in deep-sea channels, submarine canyons and other active sediment-transport systems. When seabed surfaces are undercut, this can decrease the stability by increasing shear stress and/or decreasing the shear strength. With underwater earthquakes, the earthquake-induced shear stresses are large relative to sediment shear strength because the earthquake must accelerate all the sediment column including the interstitial water. The sediment shear strength is relatively low because it builds up in proportion to the submerged unit weight of the sediment and may be even lower if there are excess pore pressures. The ratio of driving stress to resisting strength is high relative to that on land. Rapid sediment accumulation contributes to failure in several ways. Because most of the weight of newly added sediment is carried by pore-water pressures. The shear stress acting downslope increases more rapidly. The shear stress may also increase because more sediment may be deposited at the head of the sloping surface than at the toe. In addition, the following may result in failure: retarded sediment shear strength development, increased development of shear stress because of thickness of the sediment body, and increased development of shear stress because of increases in the slope steepness.

Metrics and numeric limits

Landslide sediment movement has been measured in two events from breakage of submarine telephone cables. These indicate velocities of up to 28 m/s or 101 km/h (Grand Banks, 1929) and 5 to 16 m/s (18–57 km/h) in the Strait of Luzon between Taiwan and the Philippines between 2006 and 2015.

Key relevant UN convention/multilateral treaty

Not found

Examples of drivers, outcomes and risk management

In coastal and offshore regions, submarine landslide impacts threaten submarine installations such as oil platforms, pipelines, cables, and wind installation. Mass submarine sediment failures are also one of the most important sources of sedimentation from shallow to deep-water environments and of shaping continental margins (McAdoo et al., 2000). Hence, a better understanding of submarine landslides is of great importance in the development of offshore resources exploration and protection, sustainable flood risk management, hazard assessments for engineering and environmental projects, and also in hydrocarbon reservoir managements (McAdoo and Watts, 2004; Masson et al., 2006).

Key relevant UN convention / multilateral treaty

Not applicable.

Examples of drivers, outcomes and risk management

Development of ideas and understanding of submarine landslides has been based mainly on their role in generating tsunamis, with one example in 1969 where an oil platform in the Gulf of Mexico collapsed when the soft seabed was destabilised during a hurricane. The most important historical event with significant loss of life was in 1998 in Papua New Guinea when a slump generated tsunami killed over 2200 people on the nearby coast. Other important events include the 1929 Grand Banks landslide tsunami in which 27 people died, and in 1964 during the Great Alaska earthquake, when submarine landslides in Resurrection Bay and Port Valdez caused tsunamis that killed 45 people. An additional risk from submarine landslides are submarine telegraph and fibre optic cables. As noted, in 1929 trans-Atlantic telegraph cables off Newfoundland were broken by the Grand Banks landslide, and between 2006 and 2015 submarine telecommunication cables in the Strait of Luzon were broken by turbidite currents.

References

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Coordinating agency or organisation

British Geological Survey.

GH0032 / **GEOHAZARD / Other Geohazard**

Rockfall

Definition

Rockfall is a fragment of rock (a block) detached by sliding, toppling, or falling, that falls along a vertical or sub-vertical cliff, and proceeds down slope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes (Highland and Bobrowsky, 2008).

Reference

Highland, L.M. and P. Bobrowsky, 2008. The Landslide Handbook – A guide to understanding landslides. U.S. Geological Survey Circular 1325.

Annotations

Synonyms

Rock fall (Varnes, 1978), Rock free fall, Block fall, Boulder fall.

Additional scientific description

Falls are abrupt, downward movements of rock or earth, or both, that detach from steep slopes or cliffs. The falling material usually strikes the lower slope at angles less than the angle of fall, causing bouncing. The falling mass may break on impact, may begin rolling on steeper slopes, and may continue until the terrain flattens (Sassa et al., 2018).

Metrics and numeric limits

Very rapid to extremely rapid, free-fall; bouncing and rolling of detached soil, rock, and boulders. The rolling velocity depends on slope steepness (Hungr et al., 2014).

Key relevant UN convention / multilateral treaty

Not applicable.

Examples of drivers, outcomes and risk management

Drivers for rockfall include undercutting of slopes by natural processes such as streams and rivers or differential weathering (such as the freeze/thaw cycles), human activities such as excavation during road building and (or) maintenance. Volcanic activities and earthquake shaking or other intense vibration are also drivers for rockfall (Hungr et al., 2014).

Falling material can be life-threatening. Falls can damage property beneath the fall-line of large rocks. Boulders can bounce or roll great distances and damage structures or kill people. Damage to roads and railroads is particularly high: rockfalls can cause deaths in vehicles hit by rocks and can block highways and railroads (Highland and Bobrowsky, 2008).

Mitigation measures for rockfall include rock curtains or other slope covers, protective covers over roadways, retaining walls to prevent rolling or bouncing, explosive blasting of hazardous target areas to remove the source (scaling), removal of rocks or other materials from highways and railroads can be used to minimise risk (Sassa et al., 2018).

Rock bolts or other similar types of anchoring used to stabilise cliffs, as well as scaling, can lessen the hazard. Warning signs are recommended in hazardous areas for awareness. Stopping or parking under hazardous cliffs should be warned against (Highland and Bobrowsky, 2008).

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Coordinating agency or organisation

British Geological Survey.

Landscape Creep

Definition

Landscape creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress, sufficient to produce permanent deformation, but too small to produce shear failure (adapted from Hutchinson, 1968; and Varnes, 1978).

References

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Annotations

Synonyms

Soil creep, Solifluction.

Additional scientific description

Extremely slow movement of surficial soil layers on a slope (typically less than 1 m deep), commonly as a result of climate-driven cyclical volume changes (wetting and drying, frost heave). There are generally three types of creep: seasonal creep, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; continuous creep, where shear stress continuously exceeds the strength of the material; and progressive creep, associated with slopes that are reaching the point of failure due to other types of mass movement. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (HIghland and Bobrowsky, 2008).

Metrics and numeric limits

Creep can be regional in nature (tens of square kilometres) or confined to small areas. The rates of movement are extremely slow, usually less than 0.5 m per decade (0.5 to 15 mm/yr) (Saunders and Young, 1983).

Key relevant UN convention / multilateral treaty

Not relevant.

Examples of drivers, outcomes and risk management

Rainfall and snowmelt are typical triggers for landscape creep, whereas for other types of creep there could be numerous causes, such as chemical or physical weathering, leaking pipes, poor drainage, destabilising types of construction (Highland and Bobrowsky, 2008).

Because it is hard to detect in some places owing to the slowness of movement, creep is sometimes not recognised when assessing the suitability of a building site. Creep can slowly pull apart pipelines, buildings, highways, and fences, and can lead to more significant ground failures that are potentially more destructive and faster moving than those resulting from creep alone. The most common mitigation for creep is to ensure proper drainage of water, especially for seasonal creep. Slope modification such as flattening or removing all or part of the landslide mass, can be attempted, as well as the construction of retaining walls (Highland and Bobrowsky, 2008).

References

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Coordinating agency or organisation:

British Geological Survey.

GH0034 / **GEOHAZARD / Other Geohazard**

Sediment Rock Avalanche

Definition

Rock avalanches are a translational form of mass movement where the transported material is dry rock that is fragmented before or during slope failure. They are rapid with long runouts and large volumes and often involve the entrainment of slope material, commonly therefore, giving rise to debris slides or flows. The motion of rock avalanches is massive such that the bulk of the rock fragments move together as a largely coherent mass (adapted from Collins, 2014 and USGS, no date).

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Annotations

Synonyms

Rock fall-debris avalanche.

Additional scientific description

Volcanos and earthquakes are commons triggers for rock avalanches. They can occur in all rock types but are associated with rock that is more competent. Large rock avalanches are hypermobile and exhibit more movement than predicted from frictional models incorporating air entrainment, pore pressures or fine bed layers (Hungr et al., 2001, 2014).

Metrics and numeric limits

Rock avalanches pose some of the most dangerous and expensive geological hazards in mountainous terrain. Typical of these was the Frank Landslide, which occurred on 29 April 1903, and involved 110 million tonnes of limestone released from the summit of Turtle Mountain, Alberta. The rock mass that fell was 150 m deep, 425 m high and 1 km wide (Frank Slide Interpretive Centre, no date).

Key relevant UN convention/multilateral treaty

Not identified.

Examples of drivers, outcomes and risk management

A database of 20th-century worldwide catastrophic landslides (USGS, no date) includes six rock slide-debris avalanche events, including one volcano-triggered landslide (St Helens) and three earthquake triggered landslides. The earthquake triggered events resulted in river dams with loss of entire villages Bairaman, Papua, New Guinea in 1986 and Tadzhik Republic: Usoy, 1911 and Khait, 1949.

The Frank Landslide occurred at night. It was triggered by unusual weather conditions influenced also by subsurface mining. The rockslide buried part of the town of Frank with most of the 110 people in its path losing their lives (Frank Slide Interpretive Centre, no date).

As with other types of landslide, rock avalanche can cascade to form river dams with the potential for subsequent release and flooding. Climate change impacts on permafrost have been associated with increasing incidence of rock slide initiation triggered by melting ice or thawing permafrost (USGS, 2018).

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Coordinating agency or organisation

British Geological Survey.

GH0035 / **GEOHAZARD / Other Geohazard**

Tsunami (Submarine Landslide Trigger)

Definition

Tsunami is a Japanese term meaning wave ('nami') in a harbour ('tsu'). It is a series of travelling waves of extremely long length and period. They are usually generated by seabed disturbances associated with earthquakes occurring below or near the ocean floor, but also by other mechanisms such as submarine landslides (IOC, 2019).

Reference

IOC, 2019. Tsunami Glossary, 2019. Intergovernmental Oceanographic Commission (IOC), Technical Series, 85. Fourth Edition. IOC/2008/TS/85 rev.4. https://unesdoc.unesco.org/ark:/48223/pf0000188226?posInSet=1&queryId=aeb846ae-edfb-4d66-a03a-385a5d5897f0

Annotations

Synonyms

Not found.

Additional scientific description

Tsunamis are also called seismic sea waves and, incorrectly, tidal waves. Submarine landslides, volcanic eruptions and coastal rock falls also generate tsunamis, as can large meteorites impacting the ocean. Tsunamis are gravity waves that may attain wavelengths of hundreds of miles with periods of 10 to 60 minutes; which allow them to travel across the largest ocean basins with little loss of energy. Tsunami waves steepen and increase in height up to tens and hundreds of meters on entering shallow water, inundating low-lying areas. Where local submarine topography causes the waves to oversteepen, they may break and cause great damage. Tsunamis have no connection with tides; the popular name, tidal wave, is entirely misleading (IOC, 2019).

Approximately 80% of tsunami are caused by earthquakes, but more recently it has been recognised that submarine landslides are also a significant tsunami mechanism. The size of the landslides varies from a few (one to six), to thousands of cubic kilometres. The size of the initial wave caused by the submarine landslide varies from a few to hundreds of meters. This initial wave rapidly collapses, and then travels away from the source at speeds of hundreds of kilometres per hour, depending on the water depth, with the deeper the water, the faster the velocity. There are usually a number of tsunami waves, of extremely long (hundreds of kilometres) wavelength, but small (less than one metre) elevation. When the waves approach land, and water depths shallow, they can build to tens or, more rarely, hundreds of metres in height, which can inundate low-lying areas and cause great damage. The tsunami waves caused by submarine landslides, compared to those from earthquakes, are of higher frequency so are very dispersive; unless the landslide is large volume, they do not travel as far. Near to the source mechanism, on striking land they can be elevated (tens to hundreds of metres high), and can be very destructive (Tappin, 2017, 2021).

The Intergovernmental Oceanographic Commission (IOC) uses the following terms to the describe the scale and impact of a tsunami (IOC, 2019):

Travel time: Time required for the first tsunami wave to propagate from its source to a given point on a coastline.

Arrival time: Time of the first maximum of the tsunami waves.

Inundation or Inundation-distance: The horizontal distance inland that a tsunami penetrates, generally measured perpendicularly to the shoreline.

Inundation (maximum): Maximum horizontal penetration of the tsunami from the shoreline. A maximum inundation is measured for each different coast or harbour affected by the tsunami.

Inundation area: Area flooded with water by the tsunami.

Inundation height Elevation reached by seawater measured relative to a stated datum such as mean sea level or the sea level at the time of tsunami arrival, at a specified inundation distance. Inundation height is the sum of the flow depth and the local topographic height. Sometimes referred to as tsunami height.

Inundation line: Inland limit of wetting measured horizontally from the mean sea level line. The line between living and dead vegetation is sometimes used as a reference. In tsunami science, the landward limit of tsunami run-up.

Leading wave: First arriving wave of a tsunami. In some cases, the leading wave produces an initial depression or drop in sea level, and in other cases, an elevation or rise in sea level. When a drop in sea level occurs, sea level recession is observed.

Mean height: Average height of a tsunami measured from the trough to the crest after removing the tidal variation.

Run-up

- Difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami. In practical terms, run up is only measured where there is a clear evidence of the inundation limit on the shore.
- Elevation reached by seawater measured relative to some stated datum such as mean sea level, mean low water, sea level at the time of the tsunami attack, etc., and measured ideally at a point that is a local maximum of the horizontal inundation. Where the elevation is not measured at the maximum of horizontal inundation, this is often referred to as the inundation-height.

Tsunami amplitude: Usually measured on a sea level record, it is (1) the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level at the time, (2) half the difference between an adjacent peak and trough, corrected for the change of tide between that peak and trough. It is intended to represent the true amplitude of the tsunami wave at some point in the ocean. However, it is often an amplitude modified in some way by the tide gauge response.

Tsunami period: Amount of time that a tsunami wave takes to complete a cycle, or one wavelength. Tsunami periods typically range from 5 to 60 minutes. Tsunami period is often measured as the difference between the arrival time of the highest peak and the next one measured on a water level record.

Tsunami wavelength: The horizontal distance between similar points on two successive waves measured perpendicular to the crest. The wavelength and the tsunami period give information on the tsunami source. For tsunamis generated by earthquakes, the typical wavelength ranges from 20 to 300 km. For tsunamis generated by landslides, the wavelength is much shorter, ranging from hundreds of meters to tens of kilometers.

Meteotsunami: Volcanic eruptions, submarine landslides, and coastal rock falls can also generate tsunamis, as can a large meteorite impacting the ocean. Tsunami-like phenomena generated by meteorological or atmospheric disturbances.

For more terms see (IOC, 2019).

Metrics and numeric limits

Tsunamis from submarine landslides, depending on their mechanism (slump or translational landslide) and volume can attain onland heights of up to hundreds of metres. The PNG tsunami of 1998, from a slump, attained a maximum height of 15 m. The tsunami from the Storegga translational landslide off Norway was 20–30 m on the Shetlands. Volcanic collapse tsunamis on the Hawaiian Islands are up 300–400 m high.

Key relevant UN convention/multilateral treaty

Not found

Examples of drivers, outcomes and risk management

Submarine landslide tsunamis are rare and unpredictable. They are mainly triggered by earthquakes, which often results in problems identifying the actual tsunami mechanism. They can also be triggered by volcanic activity. The primary tsunami hazard is to coastal communities within a few tens of kilometres of the source mechanism. At present, there is no management structure to mitigate the hazard, except where there is an identified associated earthquake which could act as a warning (if an earthquake warning system is in place). The identification of past submarine landslides events, from mapping of nearshore areas with steep slope gradients, could be used as a basis for identifying the potential submarine landslide tsunami hazard, on which mitigation strategies could be based. Volcanic submarine landslides can be mitigated through the monitoring of volcanic activity and from past events. In contrast to risks from earthquake-generated tsunamis, that can be managed through rapid response based on the rapid detection of tsunamigenic earthquakes, risks from, and warning of, submarine landslide tsunamis could, to some extent, be addressed by anticipatory coastal evacuations in response to earthquake warning system messages.

Primary hazards/damage. Damage and destruction from tsunamis is the direct result of three factors: inundation, wave impact on structures, and erosion. Deaths occur by drowning and physical impact or other trauma when people are caught in the turbulent, debris-laden tsunami waves. Strong tsunami-induced currents have led to the erosion of foundations and the collapse of bridges and seawalls. Floatation and drag forces have moved houses and overturned railroad cars (IOC, 2019:6).

Tsunami associated wave forces have demolished frame buildings and other structures. Considerable damage is also caused by floating debris, including boats, cars, and trees that become dangerous projectiles that may crash into buildings, piers, and other vehicles. Ships and port facilities have been damaged by surge action caused by even weak tsunamis. Fires resulting from oil spills or combustion from damaged ships in port, or from ruptured coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami (IOC, 2019:6).

Secondary hazards/damage. Secondary hazard/damage includes sewage and chemical pollution following the tsunami destruction. Damage to intakes, discharge, storage facilities and flooding of cooling generators are also major potential problems. During tsunami drawdown, there is the potential for the receding flood waters to uncover cooling water intakes associated with nuclear power plants, leading to overheating and explosion of nuclear facilities (IOC, 2019:7).

Environmental damage and damage to coastal croplands can result from deposition of sediments over inundated areas and salt water contamination. This could be a particular problem with tsunamis associated with volcanic eruptions, from the transport and deposition of floating pumice onto land, and the erosion, transport and redeposition of volcanic tephra deposited in phases of the eruption prior to the tsunami inundation. Clean-up efforts can be complicated by contamination of sediment and debris with salt and with spilt oil fuels and other chemicals.

Risk management for tsunamis: A number of guidelines on tsunami risk assessment/management are available. Examples include IOC (2015) and UNDRR (2017).

Regional Coordination and Centres: The IOC is coordinating the implementation of a global tsunami warning system, building upon its experiences in the Pacific to establish regional warning systems for the Indian Ocean (IOTWMS); Caribbean Sea (ICG-CARIBE-EWS); and the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS). The regional systems coordinate international tsunami warning and mitigation activities, including the issuance of timely and understandable tsunami bulletins to IOC Member States.

The Intergovernmental Coordination Group for Tsunamis addresses tsunami risk globally through the following groups:

ICG-PTWS Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System, formerly ICG/ITSU, was renamed by Resolution EC-XXXIX.8 of the IOC Executive Council in 2006 as proposed by the International Coordination Group for the Tsunami Warning System in the Pacific at its 20th Session in 2005 (Recommendation ITSU-XX.1). There are presently 46 Member States in the ICG-PTWS. ICG/ITSU, the International Coordination Group for the Tsunami Warning System in the Pacific was established by Resolution IV-6 of the 4th Session of the IOC Assembly in 1965. The Pacific Tsunami Warning Center (PTWC) serves as the Tsunami Service Provider (TSP) for the Pacific Ocean. Other TSPs for specific regions of the Pacific Ocean are the North West Pacific Tsunami Advisory Center (NWPTAC) and the South China Sea Tsunami Advisory Center (SCSTAC). The ICG-PTWS presently comprises over 40 Member States and oversees warning system operations and facilitates coordination and cooperation in all international tsunami mitigation activities.

ICG-IOTWMS The Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG-IOTWMS) was formed in response to the tragic tsunami on December 26th 2004, in which over 230,000 lives were lost around the Indian Ocean region. The ICG-IOTWMS comprises 28 Member States. There are three TSPs in the Indian Ocean, hosted by the governments of Australia, Indian and Indonesia.

ICG-NEAMTWS The Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG-NEAMTWS) was formed in response to the tragic tsunami on 26 December 2004, in which over 230,000 lives were lost around the Indian Ocean region (Indian Ocean Tsunami Information Centre, no date). The ICG-NEAMTWS consists of Member States bordering the North-eastern Atlantic and those bordering and within the Mediterranean and connected seas. There are currently five accredited Tsunami Service Providers (France, Greece, Italy, Portugal, Turkey) in the NEAM region providing tsunami services and alerts to subscribing Member States.

ICG-CARIBE-EWS The Intergovernmental Coordination Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG-CARIBE-EWS) was established in 2005 and currently comprises 32 Member States and 16 Territories in the Caribbean.

Tsunami Service Providers (TSPs) are centres that monitor seismic and sea level activity and issue timely tsunami threat information within an ICG framework to National Tsunami Warning Centres (NTWCs) / Tsunami Warning Focal Points (TWFPs) and other TSPs operating within an ocean basin. The NTWCs / TWFPs may use these products to develop and issue tsunami warnings for their countries. TSPs may also issue public messages for an ocean basin and act as NTWCs providing tsunami warnings for their own countries. Currently there are nine operational TSPs.

National Tsunami Warning Centres (NTWCs) are a centre officially designated by the government to monitor and issue tsunami warnings and other related statements within their country according to established national Standard Operating Procedures.

World Tsunami Awareness Day, 5 November every year: The United Nations, through UN Resolution 70/203 adopted on 22 December 2015, has designated 5 November as World Tsunami Awareness Day (UNDRR, 2020). The day aligns with the International Day for Disaster Reduction (13 October) and the seven targets of the Sendai Framework for Disaster Risk Reduction 2015–2030 (ITIC, 2020). The IOC is a key international partner of the UNDRR on World Tsunami Awareness Day.

Tsunami Ready is a voluntary community recognition programme that promotes tsunami hazard preparedness as an active collaboration among federal, state/territorial and local emergency management agencies, community leaders and the public. The main goal of the programme is to improve public safety before, during and after tsunami emergencies. It aims to do this by establishing guidelines for a standard level of capability to mitigate, prepare for and respond to tsunamis, and working with communities to help them meet the guidelines and ultimately become recognised as 'tsunami ready' by the National Weather Service. It was first implemented in the United States .To date, there are 26 IOC-UNESCO Tsunami Ready recognised communities in 18 countries and territories, excluding those implemented in the United States.

Community engagement with evacuation zones and the 'blue lines' project In New Zealand, the Wellington Region Emergency Management Office has developed the Blue Line Project in collaboration with communities in Wellington's southern coastal suburbs. In this project, the local community helps to plan evacuation routes and safe locations based on indicative evacuation zone mapping, and blue lines are painted on the road surface at the maximum estimated tsunami inundation extent. Accompanying evacuation signage is installed. Community members are engaged early in the project, publicising the work and helping to develop blue line locations, evacuation zone maps and information boards. The communities participating in the Blue Line Project can be considered to have a higher degree of public education regarding tsunami evacuation than other communities (Fraser et al., 2016). Other communities around the world have used similar community engagement strategies.

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Coordinating agency or organisation

United Nations Educational, Scientific and Cultural Organization (UNESCO), Intergovernmental Oceanographic Commission (IOC-UNESCO) and the British Geological Survey.