Earthquakes and Groundwater and Surface Water Management at Mines Sites

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Abstract

The design of water management infrastructure in mines and the assessment of the impact of proposed mining operations on groundwater and surface water typically draws on baseline studies of surface water levels and flows and hydrological investigations encompassing groundwater occurrence, piezometric levels, and the hydraulic conductivity of the identified hydrostratigraphic units. As part of the design and or impact assessment process account is taken of the current and future demands of the mine infrastructure, capturing inflows and outflows to and from the system as part of a water balance, often including the potential for increases or decreases in future water flows resulting from, for example, climate change.

Although the impact of earthquakes is taken into account in the design of structures and an assessment of the impact of major hazards from, for example, tailings dams, the impact of earthquakes on the groundwater and surface water regimes is rarely considered. The impact of earthquakes on groundwater has long been recognised (e.g. Cooper *et al* 1965), and following significant earthquakes significant changes to groundwater and surface water hydrology (e.g. [2]) can occur, including increased surface water flows and changes in groundwater levels. There changes can be of sufficient magnitude to have not inconsequential implications for mine water management.

This paper sets out the impact of earthquakes on groundwater and surface water hydrology and the potential implications for groundwater and surface water management in mines.

Key words: mine water, groundwater, surface water, earthquake, seismicity, mine

Introduction

The design of mine infrastructure, including for example tailings management facilities (TMF), pit slopes and processing plants, typically takes into account the potential risks from earthquakes and is based on long established local and international design codes. These are often codified within local legislation. The design of water management infrastructure typically draws on baseline studies of surface water levels and flows and hydrological investigations encompassing groundwater occurrence, piezometric levels and the hydraulic conductivity of the identified hydrostratigraphic units. This information also supports the assessment of the impact of proposed mining operations on groundwater and surface water. During the design process (be they feasibility type studies or detailed design) and or the completion of an environmental and social impact assessment (ESIA) account is taken of the current and future demands of the mine infrastructure typically through the development of a water balance. The water balance will capture the inflows and outflows to and from the mine site, often including the potential for increases or decreases in future water flows resulting from, for example, climate change.

However, although the impact of earthquakes is taken into account in the design of structures and an assessment of the impact of major hazards from, for example, tailings dams, the impact of earthquakes on the groundwater and surface water regimes is rarely considered, even though the impact of earthquakes on groundwater and surface water regimes has long been recognised (e.g. [1]) and significant coseismic changes to groundwater and surface water hydrology (e.g. [2]) can occur. Such changes can include increased surface water flows and changes in groundwater levels. These changes can be of sufficient scale to have not inconsequential implications for mine water management. This paper examines some of the causative mechanisms and risk factors with regards to considering the impact of earthquake seismicity on mine water management.

Groundwater Response to Earthquakes

Earthquakes generate seismic waves which have an effect on groundwater in two principal ways. Firstly they can cause oscillations in groundwater levels and secondly they may cause permanent changes in groundwater levels, where groundwater is in continuity with surface water there may be consequential impacts such as changes in surface water flow. The response of groundwater, and hence surface water, to earthquakes is complex and occurs on varying timescales and through a number of different mechanisms. The processes involved as summarised in Figure 1 below.

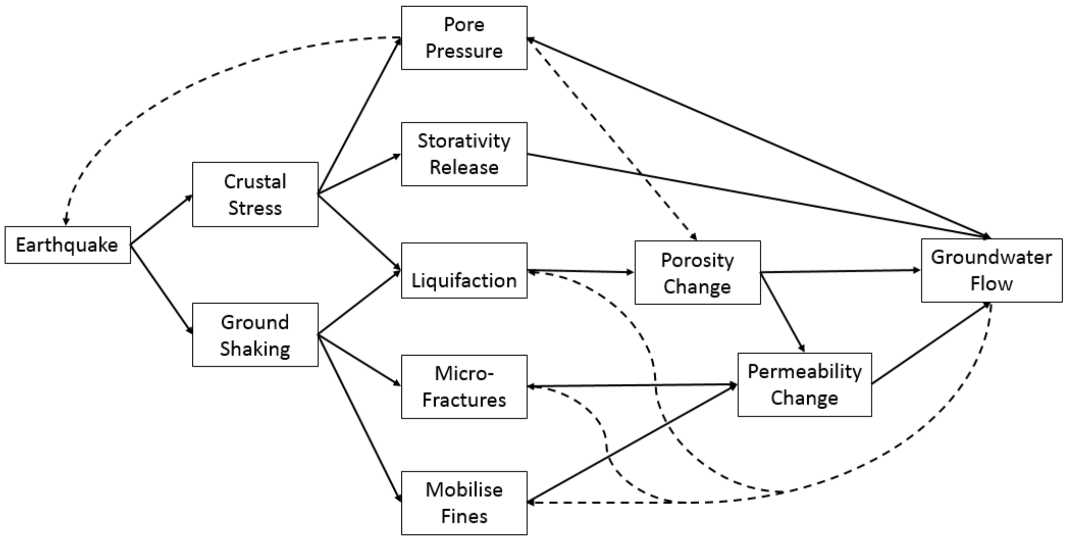

Figure 1 *Relationships between earthquakes and groundwater processes (adapted from: http://seismo.berkeley.edu/~manga/eps200-2006.html).*

The impact of an earthquake on the groundwater and surface water regime may be considered in three parts: before, during and after an earthquake.

In the area proximal to a fault zone before an earthquake there may be an increase in pore pressure (in a compressional regime) or decrease in pore pressure (in an extensional regime) as the result of poroelastic deformation resulting from changes in stress. In an unconfined aquifer, or a high permeability confined aquifer, the increase/decrease in pore pressure will be quickly dissipated and no significant effects, in terms of changes in groundwater or surface water flow, will be observed.

During an earthquake the dynamic motion (ground deformation) resulting from the passage of seismic waves will cause changes of pore pressure within an aquifer. These changes will typically occur at a frequency which does not allow for the excess pore pressure to dissipate through the flow of groundwater. Manga and Wang (2007) indicate that the cyclic dynamic stress changes associated with a magnitude 8 earthquake are on the order of 3 MPa at 100 km from the focal point decreasing to 0.06 MPa at 1000 km from the focal point. This is clearly very dependant on the geomechanical properties of the rock/soil, for example in high stiffness granites relatively small strain will give rise to large changes in stress. Understanding of changes in pore pressure associated with dynamic strain is crucial to understanding the stability impacts of an earthquake in proximity to a mine site. There are a number of geotechnical/geomechanical modelling tools that may be used to understand these changes under a given set of conditions (for example, assuming the fracture regime is isotropic, QUAKE/W or in anisotropic scenarios: ELFEN, FLAC and FracMan).

Oscillation of pore water pressures (groundwater levels) has been recorded in aquifers at very large distances (>5000 km) from the earthquake focus as a result of resonance within the well with the passage of the Rayleigh waves. While this response, which may amplify the change in pore pressure, may be of academic interest in terms of understanding the cause of oscillation or water levels in wells or understanding the magnitude of seismic response at distance from an earthquake zone in the absence of seismometers it is not significant in terms of understanding responses of structures at the site, or flows to the mine pit, as a result of earthquakes. Large amplitude fluctuations in response to distant large earthquakes could potentially damage in-situ monitoring equipment in the wells. The oscillation can be calculated using the method of Cooper *et al* (1965) as a function of dynamic strain caused by the Rayleigh wave and is dependent on the dimensions of the well, the transmisivity, storage coefficient, and porosity of the aquifer as well as the type, period, and amplitude of the seismic wave. If accurate site specific data is available regarding aquifer permeability and well construction it may be possible to assess the possible order of magnitude of groundwater level fluctuations that may occur at a mine site for a given magnitude earthquake focused at a given distance from the site. It is suggested that if groundwater level fluctuations are recorded that cannot be ascribed to other causes then it may be of value, in areas of known high seismic hazard, to asses this mechanism at such a time.

Static strain changes as a result of crustal movements occur during an earthquake, but are typically orders of magnitude smaller than dynamic strains. The effect of static strain changes are discussed further below.

Following an earthquake the static stress changes associated with crustal movements can cause poroelastic strain resulting in an increase in pore pressure in a compressional regime and a decrease in pressure in a dilatational regime. It should be noted that in strike slip fault regimes there would be both zones of dilatation and zones compression. Manga and Wang (2007) indicate that static stress changes associated with a magnitude 8 earthquake are on the order of 0.01 MPa at 100 km from the focal point decreasing to 0.0001 MPa at 1000 km of the focal point. The change in pore pressure (p) is related to the mean stress change (σ) by the equation:

$$p = \frac{B}{3}\sigma$$

Where B is Skempton's coefficient and is a variable related to the porosity and compressibility of the pore fluid, solid grains and saturated rock and has a value between 0 and 1, with 'hard rocks' having a value between 0.5 and 0.9 and unconsolidated materials having a value close to 1 (Manga and Wang 2007).

Whilst increase in pore fluid pressure as a result of coseismic strain in a compressional regime is reported to cause flow following large earthquakes, significant effects are limited to areas close to the fault zone and the equilibration period will typically be short in an unconfined aquifer. It is unlikely, for example, that the occurrence of a Magnitude 4 (M4) or M5 earthquake several hundred kilometres from a location would result in a significant increase in groundwater flow as a result of coseismic strain. Even in the case of a large earthquake in closer proximity to the mine, work by numerous authors (for example see Manga and Wang 2007) has demonstrated that coseismic strain does not contribute a significant groundwater flow and that much larger groundwater flows are typically associated with other processes.

In dilatational regimes, coseismic strain can result in large increases in permeability in the area within hundreds of kilometres of the fault zone following an earthquake causing a significant increase in groundwater discharges and fall in groundwater levels. For example Tokunaga (1999) reported a 100% increase in discharge rates declining to 50% above baseline over the first 4 months following the 1995 Kobe quake and calculate this as equivalent to a five fold increase in hydraulic conductivity. A 70 m drop in water level was observed in groundwater wells in the affected zone.

In addition to coseismic strain, there are a number of other processes which may act to cause increased groundwater flows, which may act at greater distances from the fault zone and also may act to cause groundwater response opposite to those predicted based on coseismic strain (Wang *et al* 2001). Long term step changes in groundwater level, both up and down, can occur as a result of major earthquakes close to the rupture zone, or at significant distances from it.

Dynamic stress (i.e. ground shaking) during an earthquake can cause the permanent deformation of rocks and sediments resulting in changes in groundwater flow associated with both increases and decreases in groundwater level. In the case of unconsolidated soils this may result in rapid consolidation and ultimately liquefaction. If consolidation occurs, the pore pressures in the sediments will increase, resulting in an increased groundwater discharge. In competent rocks and consolidated sediments, cyclical ground shaking may result in microscopic and or macroscopic fracturing, resulting in an increase in permeability and therefore the potential for an increase in groundwater flow. Wang *et al* (2001) reported both of these processes occurring in response to the M7.5 Chi-Chi earthquake in Taiwan.

Unconsolidated alluvial sediments may be vulnerable to liquefaction in response to earthquake movement. In various geological regimes correlations have been made between the distance from the epicentre at which liquefaction occurs and earthquake magnitude (e.g. Wang *et al* 2006). However, such empirical studies cannot be transferred directly to different locations and geological regimes. Liquefaction (as well as having severe consequences for the stability and survival of any overlying structures) will result in consolidation and increases in pore pressure. Long term changes in water level have been observed at boreholes some distance from the zone of liquefaction as a result of diffusion of the pressure front following the event.

Although it is not common, long term (6 to 12 month) changes in water level have been observed in response to earthquakes at great distance from the monitoring locations (e.g. Brodsky *et al* 2003). The mechanism for these changes are not fully understood but may result from aquifer compaction and changes in permeability changes.

Surface water response to earthquakes

Large earthquakes are often associated with changes in surface hydrology (e.g. Kargel *et al* 2016). These alterations to surface hydrology may result from physical changes in topography, damming of water courses by landslides or rockfalls and increased input of snow from earthquake induced avalanches. All of these were observed at various locations in Nepal following the 2015 Gorkha earthquake (Kargel *et al* 2016).

However other changes in surface water flows are observed that cannot be ascribed to such physical surface phenomena that are likely to be associated with changes in permeability, pore pressure and groundwater level as described above. These flows can be very large, for example an additional discharge of 0.8 km^3 was estimated following the M7.5 Chi Chi earthquake in Taiwan (Wang *et al* 2004) and a discharge of 0.5 km^3 following the M7.5 Hebgen Lake earthquake (Muir-Wood and King 1993). Other notable examples include the increase in discharge from the Alum Rock springs, California, USA following a nearby M5.5 earthquake in 2007 (Manga and Rowland 2009). Although the area over which these flows occurred is not stated, a similar response would be expected in mine flows, particularly where the mine intersects a major discharge route such as a fracture or fault zone.

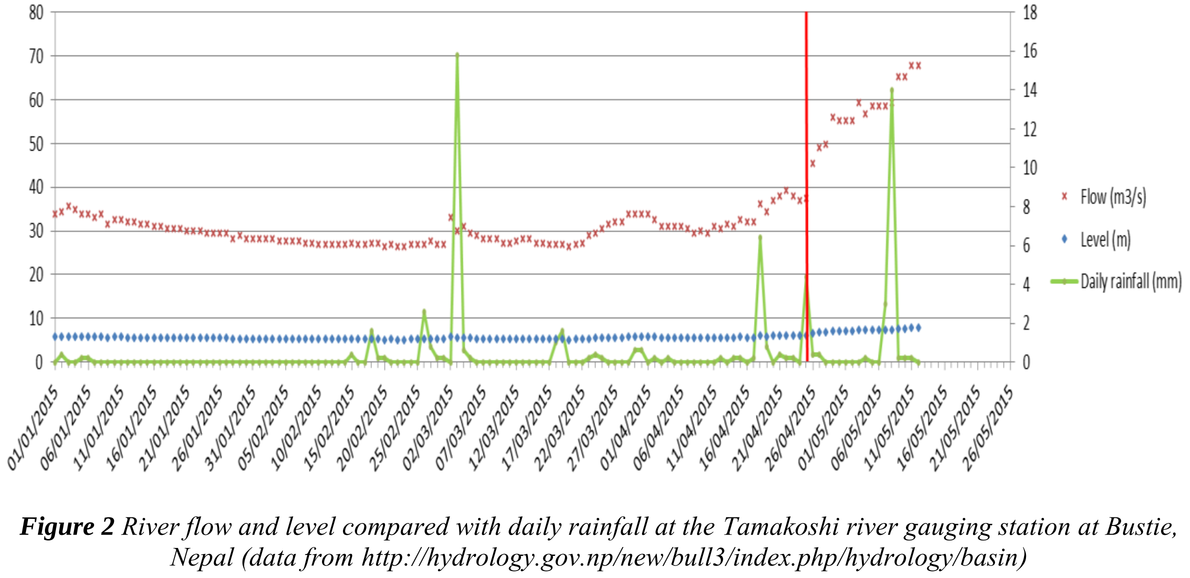

Figure 2 *River flow and level compared with daily rainfall at the Tamakoshi river gauging station at Bustie, Nepal (data from http://hydrology.gov.np/new/bull3/index.php/hydrology/basin)*

Similar increases in surface water flows were observed in Nepal following the Gorkha earthquake on 25th April 2015 (e.g. Figure 2), that occurred rapidly and are not directly ascribable to physical changes in surface hydrology/geomorphology.

Implications for Mine Water Management and Operational Resilience

Mine water management infrastructure is typically designed based on historic meteorological records and baseline monitoring of groundwater levels and surface water flows and levels. Inflow calcualtions are undertaken based on these datasets, integrated within an understanding of the conceptual hydrogeological model of the site and encompassed within a water balance, often supported by numerical models of groundwater flow and dewatering operations. At operational mines these estimates are typically refined based on operational records and experience. Should a significant change in the groundwater or surface water regime occur as a result of an earthquake, as might be anticipated in the event of a "major" (M7 – M7.9) or "great" (M8+) earthquake then the impacts on water management may be significant. It may be argued that in the event of a major or large earthquake other priorities such as the stability of the tailings dam, mine workings and process plant infrastructure may be of greater concern than water management, however should such structures be resilient to such events then ongoing water management will require consideration.

A major or great earthquake within a few hundred kilometres of a mine site could trigger increases in flow to the mine, based on the mechanisms outlined above, that may be of a sufficient rate to be a management concern (potentially many times the pre-quake inflow) as a result of:

- An increase in permeability due to fracturing in response to dynamic stress changes or dilation in extensional or strike-slip regimes;
- Increases in groundwater pore pressures in compressional stress regimes; and
- Increases in groundwater pore pressures as a result of compaction or liquefaction of overlying alluvial sediments.

Prediction of the volume of inflow as a result of each of these mechanisms is not possible due to the uncertainty regarding the type of earthquake which may occur and the static and dynamic stresses to which an area may be subject, uncertainty in the response of the rock beneath the mine site to dynamic stress changes, and uncertainty in the susceptibility of saturated soils at a particular mine site to liquefaction. With investigation and data collection, it may be possible to estimate the broad order of magnitude possible inflows for an earthquake on a particular magnitude as a response to for example liquefaction or elastic strain. However, large permeability changes have the greatest potential to influence mine water inflow, and these changes are not calculable.

As many of the impacts are not calculable it is recommended that mine water management plans at mine sites in areas of high earthquake hazard acknowledge the risk and that contingency management options are put in place. In addition to management measures contingency plans may include for the over-sizing of surface water drainage channels and ponds and or providing for additional pumping capacity to be installed as and when necessary.

Conclusions

Although oscillation of water levels in groundwater monitoring wells can occur at great distance from major earthquakes, this is a resonance effect of small changes in the aquifer and has limited implications for groundwater flow (though there may have implications for the integrity of instruments installed in the borehole). Although long term changes in groundwater level are sometimes observed in response to earthquakes at large distances from the epicentre and have the potential to be associated with increased groundwater flow due to increased pore water pressure or increased permeability, such instances are rare.

Compressional static coseismic strain can cause large changes in water level immediately following an earthquake (e.g. Manga and Wang 2007) but there is unlikely to be a significant impact on groundwater flow due to the relatively small volume of flow necessary to allow groundwater pressures to equilibrate. However major or great earthquakes can cause significant changes to groundwater levels and flows due to alterations to the permeability and changes in pore pressures. These changes will often result in changes to surface water flows.

Although earthquakes may cause significant changes to the groundwater and surface water regime at a mine site, it is acknowledged that many of the impacts are not calculable hence is recommended that mine water management plans at mine sites in areas of high earthquake hazard acknowledge the risk and that contingency management options are put in place. By way of example this could take the form of management measures or engineering measures such as over-sizing surface water ponds and or drainage channels as well as providing for additional pumping capacity to be installed as and when necessary.

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References

Brodsky EE, Roeloffs E, Woodcock D, Gall I, Manga M (2003) A mechanism for sustained groundwater pressure changes induced by distant earthquakes. Journal of Geophysical Research, 108:2390

Cooper HH, Bredehoeft, JD and Papadopulos, IS (1965) The Response of Well-Aquifer Systems to Seismic Waves. Journal of Geophysical Research, 70(16): 3915-3926

Kargel JS, *et al* (2016) Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. Science, 351(6269)

Manga M and Wang CY (2007) Earthquake hydrology, in Treatise on Geophysics, G. Schubert editor, volume 4: 293-320

Manga M and Rowland JC (2009) Response of Alum Rock springs to the October 30, 2007 Alum Rock earthquake and implications for the origin of increased discharge after earthquakes. Geofluids, 9(3): 237–250

Muir-Wood R and King GCP (1993) Hydrological Signatures of Earthquake Strain. Journal of Geophysical Research, 98(B12): 22,035-22,068

Tokunaga T (1999) Modeling of earthquake-induced hydrological changes and possible permeability enhancement due to the 17 January 1995 Kobe Earthquake, Japan. Journal of Hydrology, 223: 221-229

Wang CY, Cheng LH, Chin CV and Yu SB (2001) Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake, Taiwan. Geology 29: 831–834

Wang CY, Wang CH and Manga M (2004) Coseismic release of water from mountains: evidence from the 1999 (Mw = 7.5) Chi-Chi earthquake. Geology 32:769–772

Wang C-Y, Wong A, Dreger DS, Manga M (2006) Liquefaction limit during earthquakes and underground explosions – implications on ground-motion attenuation. Bulletin of the Seismological Society of America, 96:355–363