A Detailed Analysis of Earthquake-induced Groundwater Changes and Soil Liquefaction

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ABSTRACT

There are two causes of raised pore-pressures resulting from earthquakes, both of which may lead to geotechnical failures. The first of these, the consolidation of superficial deposits leading to loss of stiffness and ultimately liquefaction, has now been explored in detail and is relatively well understood. However there is a second, 'seismohydraulic' phenomenon that occurs when water expelled as a result of coseismic crustal strain emerges through some poorly drained unconsolidated material. Such water release leading to rising excess pore pressures is particularly significant in normal fault earthquakes and some of the largest earth flow phenomena following these events can be shown to have been caused by seismohydraulic pore-pressure increases. As this release of water from beneath the unconsolidated sediments may produce failures in materials that would not otherwise be affected by the earthquake, it constitutes an important and previously unrecognised geotechnical hazard.

INTRODUCTION

It is now generally accepted that liquefaction in a particulate material is associated with high pore pressures and low effective stresses. The loss of stiffness, and, ultimately loss of strength, that accompanies excess pore pressure rise in soils often causes permanent ground movements which have had dramatic consequences, especially when these occur within the urban environment. The source of these excess pore pressures was originally thought to be the soil itself, exhibiting a spontaneous collapse; the looser the soil the more likely liquefaction was to occur. Certainly, loose saturated soils can provide substantial excess pore pressures, but in consolidating these soils will be exhibiting stable plastic yielding, far removed from the unstable flow-type movements which are observed in the field.

On the contrary, centrifuge model tests have shown clearly that it is the combination of low effective stress and a high hydraulic gradient which is critical to the occurrence of the phenomenon generally known as liquefaction, Schofield (1980), (1981), Schofield and Steedman (1988). A loose consolidating sand layer ejects water, which in flushing upwards fractures the overlying deposits and provokes a buoyant debris flow. The fracturing of the soil by the creation of fissures dramatically alters its permeability. This breakdown of the continuum by tensile cracking has been one of the main reasons why the prediction of liquefaction has eluded numerical modellers for so long.

In design it is still common to use SPT blowcount as a measure of the liquefaction "potential" of a site although it is clear that low values of blowcount merely indicate a zone which may form one source of pore fluid if consolidation of that soil were to be provoked either by earthquake shaking or for some other reason. Any subsequent liquefaction will occur because the settling velocity of the compacting deposit has reached the terminal velocity of particles or clumps of particles in the pore fluid. In the case of a level bed clearly this velocity will be a maximum at the surface and hence the liquefaction front advances downwards, starting at the exterior (and not the interior) of the loose zone.

In general the water table (or phreatic surface) is below the ground surface. However, as the pore suctions in the capillary zone above the water table are dissipated the phreatic surface flushes upwards and will often reach the surface, leading to the discharge of water from the ground. These conditions may persist for some time after the earthquake as it takes time for the excess pore pressures to dissipate and for the solidification front, Scott (1988), to advance upwards to reach the surface.

However there is a class of phenomenon that liquefaction has never been able to explain: significant increases in groundwater flow that may sometimes continue for several months following earthquakes. These were once very widely reported, but in the 20th Century have often tended to be dismissed as part of some pre-scientific earthquake folklore. However as a result of a major study to collect empirical information on earthquake induced hydrological changes it has proved possible to find the geographical extent and magnitude of these hydrological changes. These have been shown to correspond in both extent and magnitude with crustal strain that accompanies fault rupture, Muir Wood and Woo (1991), Muir Wood and King (1991).

SEISMOHYDRAULIC PHENOMENA

Strain changes are well known from laboratory experiments to be accommodated in crustal rocks by the opening and closing of water-filled microcracks and fractures. The sign and geometry of the strain changes accompanying fault movements are dependent on the style of faulting (normal, reverse, strike-slip etc). In a region of active extension, in the interseismic period the crust is stretched, opening cracks within the rockmass, and increasing crustal porosity. At the time of the fault rupture the strain that was formerly distributed across a wide volume of the rock becomes transferred into fault displacement, and the crust surrounding the fault undergoes compressional elastic rebound (see Fig 1). In contrast in a region of active compressional tectonics, the crust decreases in porosity between earthquakes, and at the time of reverse fault displacement undergoes extensional elastic rebound. (The full three dimensional strain field of fault displacement is of course more complex than is suggested by these simple cross-sections, in particular strain of opposite sign being localised at the ends of the fault. The strain fields are also more complex around blind, non-outcropping faults and around strike-slip faults.)

In regions where there is no impermeable sedimentary cover above the crystalline basement, sudden changes in crustal porosity can be expected to communicate through to the surface. Compressional elastic rebound accompanying normal faulting will tend to raise crustal pore pressuresand cause water to rise up fractures to feed surface springs. In contrast extensional elastic rebound around reverse fault displacements will tend to draw water into the crust. This phenomenon, of changes in hydrogeology that accompany coseismic strain has been termed 'seismohydraulics', Muir Wood and King, (1991).

There have been three major (M 7) continental normal fault earthquakes in the past 35 years in regions of detailed hydrological monitoring: August 17th 1959 Hebgen Lake Montana; November 23rd 1980 in Irpinia, southern Italy and October 28th 1983 Borah Peak, Idaho. Figure 2 shows flow increases associated with these events as obtained from rivers whose catchments are located within 30 km of the fault, from Muir Wood, (1991) and Muir Wood and King (1991). These flow increases typically peak within a few days following the event and show a slow decay back to the normal flow-rates over a period of 4-12 months. (The flow data for the Italian earthquake is taken from the records of a spring, whose flow is regulated by a very large limestone aquifer. River-flows in the area were dominated by winter rainfall.) For the Borah Peak and Hebgen

Lake earthquakes it has proved possible to quantify the size of the excess discharge and its full geographical extent. Peak excess flows calculated in terms of rainfall equivalent are found to be in excess of l mm/day close to the fault, and around 0.4 mm/day at a distance of 30 km. The total rainfall equivalent discharge has a maximum of around 150 mm, but is more typically 40 rnm. The total volume of water released was found to be ca. 0.5 km3, in a period typically of 8 months, over an area of around 10,000 km2. This corresponds with the regional upper crustal volumetric strains predicted for these earthquakes of 10E-5.

When considered as their rainfall equivalents the rates of surface discharge appear relatively small, and would be easily exceeded by a daily shower of rain. Hence it might be thought that these discharges would have no significant impact on pore-pressures in superficial materials. However there are two factors that can make this seismohydraulic release of groundwater cause critical increases in pore-pressure: first its concentration, and second its emergence from beneath the superficial deposits.

The water expelled at the surface does not cause a uniform regional rise in water-tables but emerges through individual springs that overlie the major arterial fractures through the upper crust. If the daily flow of 0.4 mm rainfall equivalent from a square kilometre was concentrated at a single location this would be equivalent to 4.6 litres/sec or 400 cubic metres per day. The impact of such flows on pore pressures of superficial deposits will be determined by the available natural drainage. If this water continues to flow into a porous sand or gravel that is overlain by a relatively impermeable clay horizon then inevitably that deposit will lose its strength and begin to flow. The consequences of this will depend on location.

CASE HISTORIES

In all three of the major normal fault earthquakes whose fluvial hydrological signatures were illustrated in Fig 2, the largest debris flows appear to have been caused by the seismohydraulically induced rise in water-tables accompanying increased groundwater discharge rather than by liquefaction following immediately from ground vibration.

Following the Hebgen Lake earthquake of August 17th 1959, a long-inactive earthflow was reactivated, in the North Fork of the Kirkwood Creek, in the footwall about 10 km from the fault, Witkind et al. (1962). The flow, measuring 800 m long by 120-250 m wide, moved at least 30 m in the month following the earthquake. The gradient was on average 10 degrees but for the middle two thirds around 6 degrees. The material mobilised was soft clayey degraded bedrock. A seismohydraulic origin is preferred, chiefly because the flow did not begin moving until more than 5 days after the earthquake. The slide was located in a region in which groundwater discharges, which peaked about two days after the earthquake, were probably around i mm per day (rainfall equivalent).

Two days after the Borah Peak earthquake of October 28th 1983, in the hanging wall about 20 km from the fault there was a 200,000 m3 mud-flow in Lupine Creek, 10 km SW of MacKay, Keefer et al. (1985). The flow covered 3.5 km of the stream-valley with an average gradient less than 8 degrees. The flow was initiated by retrogressive rotational failures in silty sands mixed with clay and gravel, which having failed became mobilised as a debris-flow. The seismohydraulic origin for the flow is suggested by its timing and the very significant (>200%) increase in groundwater discharge that was noted at this time in the valley of Lupine Creek, as a result of the emergence of several new springs.

One of the largest of many slides that failed following the 1980 Irpinia earthquake was at Serra dell'Acquara, Cotecchia et al. (1986). The slide measured 2500 m long and 500 m wide, and had an estimated volume of 28 million m3. It originated along a fault boundary between the carbonate aquifer and a major aquiclude. The material mobilised was Sicilide clays overlain by broken masses of calcareous breccias. No movement had occurred in the slide over the 40 years prior to the earthquake in which time 29 houses had been built on it. A seismohydraulic explanation for the mobilisation is favoured by the timing of movement. This began with some cracking 15 hours after the earthquake but it took two weeks for the whole slide to become mobilised. A number of other large slides in the Irpinia region also became mobilised at some interval following the earthquake. A 10 million cubic metre slide on the banks of the River Sele, close to Caposele (where the spring-flow measurements were taken) was only mobilised three weeks after the earthquake, when it destroyed a road, electricity transmission lines and some rural houses, Cotecchia (1981). Some earlier rotational slides triggered by the ground shaking became subsequently remobilised as mudflows (as at Calitri), apparently as a result of saturation from increased spring flow.

COMPARISON WITH LIQUEFACTION OF SUPERFICIAL DEPOSITS

The chief way in which these phenomena can be distinguished from failure in response to vibration induced liquefaction is a result of timing. Liquefaction induced failures caused directly by consolidation of superficial deposits will occur during or for a short period after the end of ground shaking as the drainage paths for shallow deposits are short and the fissuring will have greatly increased the local permeability. In contrast the rate at which seismohydraulic effects communicate with the surface is determined by upper crustal permeabilities. Typically peak discharge occurs within 2-10 days of the earthquake. However there is a distinct class of seismohydraulic phenomena that result from high levels of strain along the fault-plane itself and which is directly comparable to a liquefaction of the superficial deposits. In these events water is forced out at the surface under considerable artesian pressure within a few minutes of the earthquake, probably as a result of spontaneous hydrofracture. One such water-burst following the Borah Peak earthquake had a peak discharge of more than 10 cubic metres per second, one hour after the earthquake, Wood et al. (1985). Such effects are however only found in the hanging wall of a dipping fault within a few kilometres of its surface trace. Although the regional increase in groundwater flow is most pronounced in normal fault earthquakes, significant increases are also found accompanying strike-slip and reverse fault earthquakes although distributed in different regions around the fault, and with lower (rainfall equivalent) magnitudes of discharge than are encountered in normal fault earthquakes. Even relatively small normal fault earthquakes have the potential to cause significant changes in groundwater flow and the level of the water-table. One M 4.5 earthquake near Colchester England in 1884 caused both a localised outburst of water at the surface and a rise in the regional chalk water table of more than 2 m, that lasted several months.

ENGINEERING IMPLICATIONS

Where any major eruption of water occurs beneath overburden it would be very likely to be mobilised into a flow-slide. The hazard will be particularly concentrated where there has been recent sedimentation or where the overburden has been dumped into its present position by man, as in the construction of a mine spoil tip, a road embankment or earthfill darn. Site investigations which relied on blowcount in superficial deposits would clearly be insufficient to comprehensively assess the likelihood of permanent ground movements at a site, particularly where landslides were concerned. Liquefaction induced flow-slides are only one manifestation of the problem, however. Any additional increase in pore pressure in the near surface deposits will result in a degradation of shear stiffness and consequential permanent strain. Where this is not accounted for in the design of a structure there could be serious consequences, for example in the permanent movement of a bridge abutment or differential settlement of an industrial facility thought to be constructed on "non-liquefiable" foundations. Remedial measures to achieve levels of drainage satisfactory to ensure the stability of major landslides or embankments may be not be sufficient where sub-slide spring-flows undergo major increases in discharge following a nearby fault movement. Increased pore-fluid pressures, following an earthquake may also affect underground structures. A number of mines have been subject to increased water flows following an earthquake. The Clayton silver mine in Idaho, located in the hanging wall 25 km from the surface trace of the Lost River Fault had to be temporarily abandoned following the Borah Peak earthquake as a result of large inflows of warm water, Wood et al. (1985) . Such problems could also affect road or rail tunnels in which the pumping capacity may be insufficient to cope with an unexpected increase in seismohydraulic groundwater flow. These phenomena are of particular significance to the siting of repositories for toxic and radioactive waste, in particular in saturated-zone crystalline rock, Muir Wood and King (1991). Seismohydraulic effects may have the potential to temporarily short-circuit the contaminated groundwater up to the surface as a result of increased pore-pressures or dilatational strain as fractures that were previously closed may become channels for fluid flow.

CONCLUSIONS

Hence in defining the stability of a site, slope or embankment or in exploring the long-term hydrogeology of a subsurface tunnel or repository it is necessary to explore not only the potential for liquefaction caused by consolidation of superficial deposits but also the potential for increased pore pressures resulting from sub-surface strain. Those locations subject to fluid expulsion following earthquakes may be characterised by the presence of certain forms of mineralisation (such as travertine), craters/fissures or areas of unexplained elutriated soils. The locations most susceptible to such processes can also be predicted by strain models of coseisrnic faulting. This is a significant and previously unrecognised hazard that has implications for a wide range of site investigations in areas of active tectonics.

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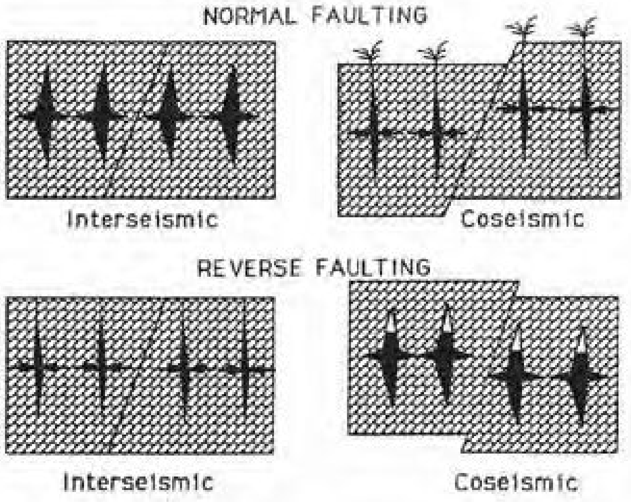

Figure 1 Simplified model for the interseismic accumulation and coseismic release of strains in extensional and compressional tectonic environments

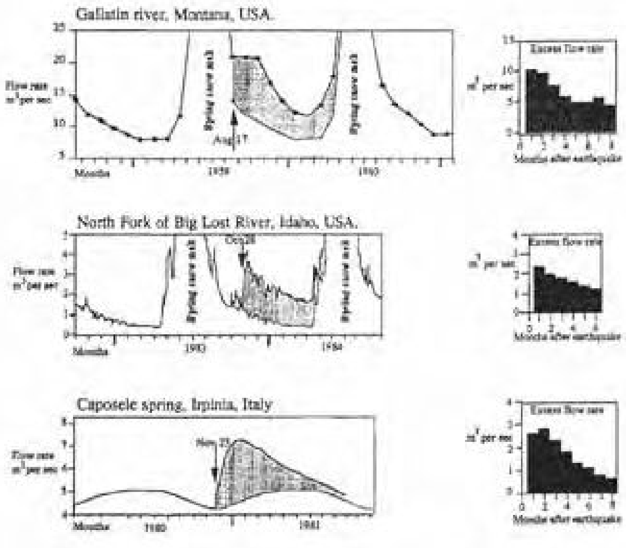

Figure 2 Fluvial hydrological signatures for three major normal fault earthquakes showing seismohydraulically induced rise in water-tables

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