EARTHQUAKE INDUCED SOIL-GROUNDWATER INTERACTIONS

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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 the possibility of liquefaction. 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. 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, 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 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, 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.

SEISMOHYDRAULIC PHENOMENA

Strain changes are well known from laboratory experiments to be accommodated in crustal rocks by the opening and closing of water-filled micro-cracks 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 rock-mass 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. 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.

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 pressures and 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 co-seismic strain, has been termed ‘seismohydraulics’. 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. 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 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 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 hydro-fracture. 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 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.

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 dam. 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 subslide 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. 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. Seismohydraulic effects may have the potential to temporarily short-circuit the contaminated groundwater up to the surface as a result of increased pore pressures 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) and craters or fissures. The locations most susceptible to such processes can also be predicted by strain models of faulting. This is a significant and previously unrecognised hazard that has implications for a wide range of site investigations in areas of active tectonics.