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Geotechnical consequences of ground motion: hazard perspectives

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Abstract

Following the 13 April 1992 Roermond earthquake, areas of the Netherlands experienced severe shaking and suffered ground failures, particularly ground cracking, sand injections, and shallow local landslips. Such phenomena are well documented in historical case histories of large earthquakes in many areas of the world: famous examples of widespread failure are reviewed and the key phenomena identified, e.g. Assam (1899) and Alaska (1964). The geotechnical conditions and consequences resulting from strong ground motions are emphasized and important applications in earthquake hazard assessment are discussed in the context of readily available literature.

Liquefaction and kindred state changes leading to masss failure, settlement, and flow-slide behaviour are considered for cases of water-saturated sandy and silty deposits. A simple classification is required to facilitate discussion of strong motion domains; these being nearfield, proximal farfield, and distal farfield. Volume changes, dewatering and displacement patterns provide insights into hazard assessment applications, amongst which three are considered: (i) intensity scaling effects, with a scheme appropriate to north-west Europe, (ii) *in situ* measurement by Standard and Cone Penetration Tests (SPTs and CPTs), and (iii) palaeoseismology. The potential of finding palaeoliquefaction phenomena in the southern Netherlands is considered to be high in the vicinity of certain faults. The importance of palaeoseismology is evaluated with relevant world-wide research perspectives regarding palaeoliquefaction. Recommendations are given to encourage research initiatives.

Introduction

On 12 June 1897 one of the modern world's great earthquakes occurred in Assam, north-west India. Although predating modern instruments, magnitude estimates can be made (probably in excess of M = 8.5) and ground accelerations exceeding that of gravity have been estimated (Oldham 1899, Richter 1958). The area of serious damage, i.e. 'high intensity', exceeded 400 km in radius. The geotechnical consequences, as recorded by Oldham in his superbly illustrated account, were numerous and on a staggering scale. Close to the source fault, ground damage was attributed to displacements, but the fountains and cracking of the flood plain deposits of the great Brahmaputra River and landslides on the slopes of the Assam hills bore witness to significant levels of shaking and ground failure at great distances. Buildings were reduced to, as reported by Oldham, 'three degrees of ruin' at Shillong. Tombstones rotated and sank at Cherrapunji and great landscape level changes were detected between survey stations near Rowmari.

Whilst such consequences are commonly associated with great earthquakes, similar phenomena are detectable in the near-source areas of smaller (modest) shallow earthquakes. Although landscape changes are less dramatic and restricted to areas of surface displacement along fault traces, ground failures due to shaking are frequently observed at significant distances from the source (Tinsley et al. 1985, Vittori et al. 1991). Thus it is not surprising that, following the 13 April 1992 event, the weaker geological formations and architectural elements in the vicinity of Roermond displayed damage characteristics seen in areas affected by great earthquakes.

Table 1. Earthquake-induced liquefaction ground failures

Phenomena
• Loss of bearing capacity (strength)
• Settlement (subsidence)
• Lateral spreading (horizontal movement)
• Slumping (rotational movement)
• Ground cracking (fissuring)
• Dewatering (post-liquefaction)
• Injection and extrusion (post-liquefaction)
• Soft-sediment deformation (post-liquefaction)
Importance
• Foundation design (codes, special structures)
• Shallow soft-ground landslides
• Groundwater flow
• Pre-historic (palaeoseismicity) records
• Hazard analysis (catalogues, ground motion estimates, liquefaction and displacement potential, e.g. slide, subsidence)

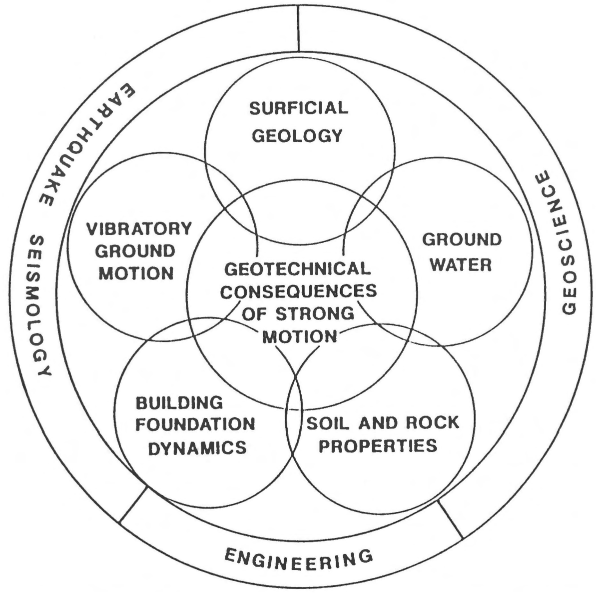

Fig. 1. Principal disciplinary components contributing to the understanding of earthquake strong motion-induced ground phenomena.

In terms of ground failures the geotechnical potential for the phenomena and processes, say in the flood plains of the Roer and Brahmaputra, are more or less the same, subject to the scale of the geological and geomorphological setting. However, in terms of the strength, duration and frequency of strong ground motion to which the geotechnical situations are likely to be exposed within a human lifespan or design life of an engineering structure, these two areas are very different. In other words, the geotechnical consequences of given levels of strong motion are almost universal and, therefore, similar in areas of similar geotechnical character (e.g. liquefaction susceptibility), whereas the potential for earthquake-induced geotechnical changes varies locally with the degree of exposure to critical levels of groundmotion (e.g. liquefaction opportunity). Therefore, on the basis of common knowledge of the differences in seismotectonic potential and extent of unconsolidated Quaternary deposits between these two areas, the Brahmaputra basin is more likely to suffer extensive large-scale ground failures than the Roer basin. These site vulnerability and hazard assessment considerations are central to the requirements of engineering geologists and seismologists involved in the design and planning of development and energy projects.

For the purposes of this commentary, one of the most important geotechnical consequences of earthquakes – liquefaction and association ground deformation – has been singled out for further consideration. The main earthquake-induced liquefaction phenomena and their importance to science, engineering and planning are listed in Table 1. The principal disciplinary components contributing to the understanding of earthquake strong motion-induced ground phenomena are given in Fig. 1. The basic aspects of geotechnical engineering, such as soil and rock properties, through flow of water, settlement and consolidation, retaining structures, slope analysis, foundations and settlement, and soil improvement and treatment are well understood (Terzaghi & Peck 1967, Lee et al. 1983). Strong ground motion measurement, soil dynamics and, in particular, case histories and site specific quantification of soil amplification, liquefaction susceptibility and liquefaction opportunity, are well documented (Das 1983, Bullen & Bolt 1985, Tinsley & Fumal 1985, Fumal & Tinsley 1985, Tinsley et al. 1985, Rosenblueth 1986, Boore & Ambraseys 1993). Less well understood and documented are the general geotechnical conditions and consequences of earthquake liquefaction, and the relationships of phenomena and geotechnical behaviour contributing to site vulnerability (Seed 1970, Cotecchia 1987, Reiter 1990, Coburn & Spence 1992).

The following commentary has been devoted to liquefaction and hazard assessment in response to the needs of the Veldhoven workshop of January 1993. The importance of palaeoseismic data, particularly palaeoliquefaction aspects, is emphasised, being central to the research interests of the author (Davenport & Ringrose 1985, Davenport & Ringrose 1987, Davenport et al. 1989, Davenport et al. 1994).

General geotechnical conditions and consequences

Liquefaction and the associated ground failures during and following earthquakes are responsible for damage levels which are just as significant and catastrophic as damage caused by the shaking of building structures. Indeed the now classical pictures of the intact apartment blocks in various states of rotation and foundering within liquefied and disturbed cohesionless foundation soils at Niigata, Japan, following the 1964 earthquake, will always be a prime example. Less well known, but equally costly, were the flowslides, bulkhead failures, embankment and fill failures on weak foundations, and lateral movements of bridge abutments (Seed 1970, Okamoto 1973). Other potentially costly results are floating of buried structures, major landslides, and failure and significant lateral deformation of dams and similar embankment or dike structures (Coulter & Migliaccio 1966, Seed & Idriss 1967, Youd 1971, Seed et al. 1969, Seed 1979, 1983, Tinsley et al. 1985, Wilson & Keefer 1985, Cotecchia 1987).

Subsurface conditions most commonly reported to exhibit instability and associated structural damage, in the literature cited here, are the following:

- geological competence, i.e. incompetent unconsolidated and poorly consolidated water saturated sediments are most vulnerable;
- groundwater table depth, i.e. incompetent sediment units saturated below shallow (generally permanent) water tables;
- unit thickness, i.e. in areas shaken strongly (generally by large shallow earthquakes) incompetent deposits of some thickness are most susceptible;
- inclination, i.e. when lateral constraint is limited or diminished and sediment masses have shear strengths and potential failure surfaces with properties (angles) close to static sliding resistance values.

The areal patterns of damage to ground and foundation structures, when reported in sufficient detail following great or critically-located events, are often seen to reflect the local geological and geotechnical elements in those areas subjected to strong shaking. Moreover, the proximity of these areas to the centre of strongest ground motion may be seen to influence ground failure patterns. To date, intensity zoning and vulnerability studies for purely ground response has not reached the same degree of sophistication as zoning and vulnerability of intensity of building damage. The standard intensity scales (e.g. MSK, MM) include ground failure and behaviour criteria in diagnostics of higher intensity grades, which have received little attention in the past (Serva in press). Within the past few years vulnerability function diagnostics of ground failure have been acquired in the field for use by seismologists in compiling hazard scenarios, and for use by geologists in the identification of palaeoseismicity. Engineers and geotechnicians are showing increasing interest in applying the results of such studies to the siting, design and construction of buildings and critical facilities. As in the case of surface (crustal) deformation, it is important to distinguish between the effects of surface fault movements and the effects of vibratory ground motion. Awareness of the significance of finite strain patterns and their field locations is required, also unambiguous diagnostic criteria should be developed for the particular terrain under investigation. In general only larger earthquake ruptures reach the surface. Vibratory ground motion effects, such as *in situ* liquefaction, dewatering injections and expulsions, settlement and ground cracking are commonplace in near-source floodplains, whilst landslides and ground buckling dominate areas of strong topography. The surface manifestations are well documented in the literature; however, subsurface phenomena are less well appreciated. Great earthquakes have provided the most spectacular examples of geotechnical failures. Opportunities to detail and quantify phenomena are also provided by more modest earthquakes in less active but susceptible terrains with smaller more accessible areas of ground disturbance.

Ground cracking and spreading

When a great fault ruptures during a large event, movement at the surface often occurs. In general, shallow fault ruptures producing earthquakes of magnitudes greater than 6 will have surface displacements which are of sufficient size (greater than 10 cm) to be seen in rocky ground (Slemmons 1977, Taylor & Cluff 1977, Yeats et al. 1981, Bonilla et al. 1984). In recent sedimentary deposits, e.g. flood-plains and lake basins, surface faulting can be distributed, creating patterns of ground cracks similar to those created by secondary (geotechnical) failures. Secondary and branch faulting, up to several kilometres from the main fault zone, can increase the complexity of ground cracking. Secondary soft-sediment cracking, triggered by fault displacements, can occur, as do landslides and incipient slope failures backed by active fault planes.

Ground cracking which results from secondary failures induced by shaking is more widespread. Lateral spreading and slumping of weak sedimentary bodies, such as flood plain deposits, are frequently identified from characteristic patterns of ground cracking. Mass movement on 'failure surfaces' is generally assumed. Loss of shear strength at depth by shaking of sand bodies (liquefaction) and clays (thixotropy) creates conditions where gravitational component forces can act to cause ground failures on all scales from incipient (maybe ground cracking) to total translational failure (perhaps with backscar ground cracks preserved).

Spectacular ground cracking can be seen when more competent top layers are underlain by weak zones, e.g. frozen crusts of saturated alluvium (Alaska, 1964), persistent uniform clay cap on loose sand (Venezuela, 1989; Roermond, 1992). In Alaska, ground cracks formed during the earthquake over an area approximately the size of the State of California (McCulloch & Bonilla 1970). Most ground cracks, apart from those associated with landsliding, occurred in granular water-laid deposits and fans, deltas, flood plains and tidal flats. The most severe cracking occurred in low-lying active flood-plain terraces located nearly at the watertable. Inactive flood-plain terraces in these same areas (the tops of which stand somewhat higher above the watertable) were considerably less fractured. The watertable is estimated to be less than 3 m below the surface in the areas of most severe cracking. These most vulnerable areas are often along the margins of streams, gullies and other topographic depressions. Stress in response to a subsurface permanent lateral displacement and spreading of the underlying sediments towards the free surface of depressions was invoked by McCulloch & Bonilla (1967), based upon reconstructions of strains in linear features such as embankments and rails. Crack patterns include tensional failure parallel with river banks and complementary shear fractures, in a classical geotechnical array. Inside meander bends and on small islands, crack patterns were akin to those of orthogonal thermal contraction cracks in frozen ground. These may be due to local geometries or inherited from cryogenic phenomena. The term 'landspreading' has been proposed for these phenomena, not necessarily associated with slopes or liquefaction, and model studies of foundation failure have been used to confirm some of these observations (McCulloch & Bonilla 1967). The horizontal and vertical movements at depth within sediments can be estimated by comparing pre and post earthquake positions of piles. However the assumptions required are problematic, hence model studies are required. Sandbox experiments show that many of the movements of materials predicted by sliding and water level changes are similar to those observed at the surface or inferred from pile displacements (McCulloch & Bonilla 1970). However, it is important to note that the fact that the ground behaviour can be influenced by the nature and behaviour of the structures, now widely recognised, was not considered. Oldham (1899) described similar major phenomena during the Assam Earthquake of 1897, as did Fuller (1912) for the New Madrid event of 1811. These early authors attributed stream channel width decreases to block gliding of a soil mass on 'daylighting' horizontal incompetent layers. Upward movement of stream channel bottoms is also observed in great earthquakes such as Assam (Oldham 1899) and Alaska (McCulloch & Bonilla 1970). Indeed, Oldham reports that during the Assam earthquake, the bottoms of channels were forced upwards until level with the banks on either side of the River Brahmaputra. During the following dry period the drainage flowed at levels close to the general land surface in shallow sandy channels. Oldham suggested the presence of loose sand beneath the river bed, which was forced upwards during earthquake shaking. Mounds of sand ejected with ground water from cracks in the floor of the streams on Hunter Flats (Alaska) are reported by McCulloch & Bonilla (1970). Such vertical and horizontal displacements have been widely reported following great earthquakes. Kindred phenomena are not so well documented from more moderate events, but undoubtedly occur within the near-source area of strongest shaking. Until 13 April, 1992, the Netherlands had not been a likely candidate for such reports, but the near-source area south of Roermond provides near-perfect geological conditions for such behaviour (Davenport et al. 1994).

Mass movements and flow-type failures

Incomplete landsliding by limited block gliding, sometimes called 'lurching', can also produce extensive cracking. Sliding on a low-angle weak stratum of clay or liquefied sand is frequently suggested (Oldham 1899, Fuller 1912, Hansen 1965). Mudflows on slope angles less than 0.5° have been recorded (Prior & Colman 1978). Therefore failures triggered by shaking in media susceptible to strength changes during cycles of strong motion, such as sensitive clays, could be envisaged in nearly horizontal strata. However, vulnerability also increases with slope angle and slope height (Keefer 1984, Cotecchia 1987). Lurch cracks are less well documented, being attributed to horizontal vibratory forces induced by seismic surface waves. McCulloch & Bonilla (1970) used evidence from pile displacements to conclude that lurching and shallow block gliding was not an important mechanism in Alaska (1964), because the horizontal displacement of the surface material did not exceed that of the underlying material.

Fully developed land and submarine slips (slumps, slides and flows) can be triggered by strong earthquake shaking. Shallow earthquakes accompanied by surface rupture and secondary surface displacements are the main contributors to earthquake-induced mass movements, particularly where the slope aspect has the potential for topographic amplification of triggering motions. General reviews with famous case histories have been published by Seed (1968), Radbruch-Hall & Varnes (1976), Keefer (1984) and Cotecchia (1987). Valuable in-depth studies include those published by Heezen & Ewing (1952), Davis & Karzulovic (1963), Hadley (1964), Plafker & Erickson (1978), Spudich & Orcutt (1982), Howard (1983), Wilson & Keefer (1983, 1985), Cotecchia (1986), Hasegawa & Kanamori (1987) and Dawson et al. (1988). Such published data provide relationships between slope height, angle, runout distance, debris geotechnics and levels of ground motion which are now used widely in earthquake hazard assessment and design.

Following cyclic strain and subsequent liquefaction, monotonic 'steady state' deformation can take place as flow-type failure when non-cohesive deposits are sufficiently loose to exhibit contractive behaviour during shear stress application (Ishihara 1993). Relative density levels control the possibilities of contractive behaviour. The initial density conditions are likely to be modified by both lateral spreading and slope-induced synliquefaction deformations achieved through grain packing changes and dewatering. Further flow-type failure is encouraged by such changes. The field phenomena diagnostic of such failures are well documented, e.g. ground cracking, graben faulting and slumping at Turnagain Heights (Alaska Great Earthquake of 1964) and Rio San Pedro (Chile Great Earthquake of 1960). In less seismic areas where even the rare events impose relatively low ground accelerations on young alluvial and reworked (mined and engineered) deposits, the most susceptible areas below the watertable may spread 'downslope' in flow-like failure, whilst the drained materials above the watertable may accommodate the horizontal spreading by failing in a quasi-brittle manner to produce small 'back-scar' faults, slumped blocks, toe bulges and fractures. Very loose and loosened sandy deposits may dewater with upward flow of sand as dikes, fountains and 'volcanoes', as seen at the Brunssummerheide after the 1992 Roermond event (Maurenbrecher et al. 1994, Alkema et al. 1994).

The two main effects of surface waves rolling through surficial deposits are commonly considered to be: 1) a structure will respond and create local stresses in the foundation materials, and 2) variations in pore water pressure occur within sediment layers resulting from seismic wave displacements. In cases of great earthquakes, where severe shaking occurs over large areas and for durations of minutes, dynamic displacements due to the passage of surface waves could contribute to the build up of excess pore-water pressures (increasing liquefaction potential) and also create cracks which would relieve such pressures (encouraging ground water and sand ejection and reducing liquefaction potential). In the near-source area of more modest earthquakes, the relatively strong vertical component of motion will rapidly vary the overburden pressure. Under these conditions, fewer cycles of strong motion with a high peak acceleration would rapidly change liquefaction potential and potential for dilation, with increase in layer strength. The ability of the ground to flow and fracture almost simultaneously under these conditions may explain local cracking and liquefaction at Roermond. The orientation and pattern of fractures may be related to surface wave motion direction, pre-existing anisotropies and/or critical landspreading-induced stresses.

Ground motion domains

Since the Long Beach (1933) and El Centro (1940) earthquakes, many more strong motion records have been obtained worldwide. Indeed, sufficient information is now in the public domain for the production of attenuation laws which are specific to soil and rock characteristics, tectonic and geographical regions, and even earthquake depth and source characteristics. Key works on strong motion attenuation include Dono-

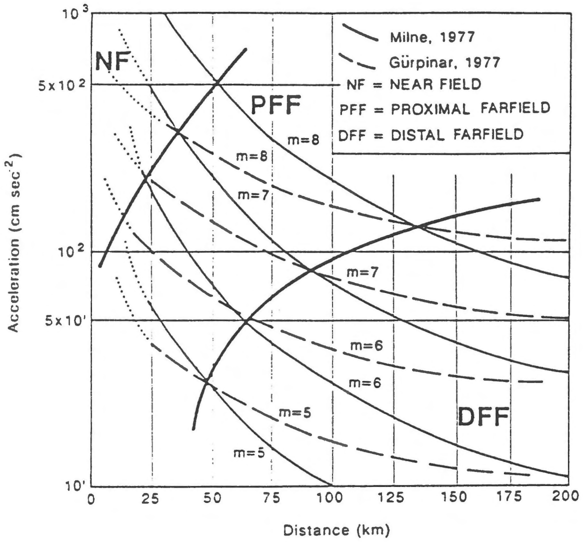

Fig. 2. Shallow focus earthquake acceleration attenuation in terms of magnitude of great (m > 8.0), large (8 > m > 6.8), and moderate (6.8 > m > 4.7) earthquakes and strong motion domains (Milne 1977, relationship for essentially rock sites; Gürpinar 1977, relationship for essentially soft ground sites).

van (1973), Nuttli (1974), Trifunac & Brady (1975), Gürpinar (1977), Milne (1977), Murphy & O'Brien (1977), Idriss (1978), Hays (1980), Campbell (1981), Joyner & Boore (1981), Seed & Idriss (1982), Joyner & Fumal (1985), Krinitzsky & Chang (1988) and Ambraseys & Bommer (1991). For state-of-the-art reviews the reader is recommended to read Ambraseys (1988) and Reiter (1990).

Three regimes of strong motion are proposed here, as shown in Fig. 2:

a) The nearfield (NF) where shallow earthquakes (which may be of modest to low magnitude) create peak acceleration records characterised by high peak acceleration values, short duration (ca. 5–10 seconds) and high frequencies (ca. 1–5 Hertz). Close to source volumes, certain peak vertical accelerations (pvga) exceed horizontal components (phga), e.g. 1.7 g pvga, 1.4 g phga close to the Imperial Fault in California (1979).

b) Proximal far-field (PFF) of shallow earthquakes, extending to distances of typically 150 km from surface source areas. Horizontal accelerations exceed vertical components and values attenuate to virtually inconsequential levels beyond 100 km for most large shallow crustal earthquakes. Durations increase with distance to tens of seconds and frequencies decline.

c) Distal far-field (DFF). Great and large earthquakes, such as those in subduction zones, which can be very deep, have greater ranges and very different attenuation characteristics. The resultant ground motions over hundreds of kilometres may be of great duration (say minutes); peak acceleration values may increase locally due to amplification in geological units with natural periods coinciding with those of the surface motions, e.g. 1.5–2.0 seconds period: Vrancea (1977) and Mexico City (1985) respectively.

The size of the fields a, b and c in Fig. 2 varies with the relative location and scale of the rupture, e.g. Loma Prieta (1989) compared with Mexico City (1985). The modest shallow earthquakes of northwest Europe can be considered to have typical near-field radii of a few kilometres, hence significant levels of motion would fail to reach the surface except in the case of the shallowest and most favourably located ruptures. The proximal far-field motions for a shallow 5.5 <m <6.5 would be characterised by local amplification in sensitive deposits, with acceleration values equivalent to MSK intensities of VI (common), VII (locally), and VIII (occasionally) in the near-source areas. Somewhat greater equivalent maximum nearfield radii and maximum intensity are reported for southern Europe, e.g. Italy (Margottini et al. 1992). The typical larger 15 km-deep northwest European earthquake ground motion intensity range and distribution is seen in the Roermond (1992) event data, with near-source liquefaction and dewatering, and perhaps, less-near, proximal far-field intensities amplified slightly at susceptible localities to create geotechnical conditions conducive to dike failure and shallow slump slides in natural and man-made materials (Ahorner 1993, Nieuwenhuis 1994, Davenport et al. 1994, Maurenbrecher et al. 1994, Lindenberg et al. 1994).

Co-seismic and post-seismic behaviour

In terms of geotechnical behaviour, similar sequences of failure take place in many environments. Level ground where loose materials are in subsaturated conditions will experience settlement when grains and voids are rearranged. Whatever the pathways of strain, the end result is loss of bulk volume. Settlement and subsidence accompanies most material change following strong shaking; however, mass movements may result in local bulging and uplift. Loose sands will compact; denser sands may dilate before compacting. Once dynamically-triggered responses such as liquefaction come to an end, rapid initial monotonic (secondary) deformation in masses can result in similar geotechnical behaviour, e.g. 'strain hardening' with brittle shear and 'softening' with water expulsion. Liquefaction on level ground in natural and artificial materials permits land (lateral) spreading with concommittent development of slip planes and macroscopic finite displacements. Even when level ground cannot spread, surface wave-induced oscillations create conditions leading to settlement, fissuring and water expulsion. Liquefaction on sloping ground creates opportunities for large displacements and reduction of shear strength in non-similar materials such as sand and sensitive clay layers. Flow slides and rotational block slides become possible. Local dewatering and transport of materials (such as sand) upwards to the surface along fissures is common. Sand volcanoes, spring pits and mounds on all scales may be found at the surface in areas of liquefaction, settlement and landsliding. 'Quick' conditions can be created by upward movement of ground water such as occurs in tidal flats. Once disturbed, the fragile 'overloose' fabric collapses, and trapped water sustains excess presures before being dissipated.

The sequences of strains which take place at depth within layered deposits can be inferred from studies of the complex structures seen in excavations after an earthquake. Some of the most spectacular soft-sediment deformations seen in drained reservoir sediments and late glacial lake deposits can be attributed to such processes (Sims 1975, Ringrose 1989). Liquefaction of sandy materials is the most studied geotechnical process leading to loss of shear strength and catastrophic failures of weak geological and artificial deposits; however, thixotropy of clayey materials is also important but less frequently reported (Boswell 1961, De Sitter 1964). In the following section, only liquefaction has been considered in detail.

For sandy ground to liquefy the surficial geological units need to be saturated and subjected to strong vibration. The fabric of the material changes as a result of the dislocation of particles created by short-term pore pressure increase in response to oscillatory grain motion. The shear strength of the body resisting the internal dynamic shear forces can be, as a first order approximation, considered to be proportional to depth-created confining stresses. Ground motion shear stresses can be considered to be largest close to the surface and liquefaction may well take place at shallow depths. At some depth the confining stresses become large enough to inhibit liquefaction. Usually, the most susceptible layers are those of loose uniform fine sand but some medium sands and silts exhibit high levels of susceptibility. Cohesion in finer materials, whether due to the presence of clays or bonding/cementing, strengthens the deposit and coarse grain sizes create connecting void systems with permeabilities sufficiently high to dissipate excess pore pressure fast enough to prevent critical weakening. Accordingly, coarser sands and those with clay contents rarely liquefy for any significant length of time, hence damage is rare and light in areas with such conditions. The spectacular liquefaction damage which occurred during the well-studied Niigata earthquake of 1964, required not only significant duration of strong motion cycles, but also alluvial sand layers (with much fine sand) and disturbed ground (300 year old fills) to thicknesses of over 100 m. Although the watertable was generally less than 2 m below the general ground surface, on the basis of changes in N-values from standard penetration tests, failure is believed to have been initiated at depths of 10–15 m. In such favourable circumstances, liquefaction could then progress to greater depths as shaking continues or initial critical pore pressures are increased; also upwards toward the surface by dewatering of the initial liquefaction zone and more local buildup of critical excess pressures. Movement of foundations, e.g. piles, could transfer the dynamic conditions encouraging liquefaction to other locations within the body. During the earthquake, several bridges across the Shinana river in the city area of Niigata were damaged in areas of liquefaction. Lateral bending measured in steel piles and lateral movements of several metres towards the river are indicative of flow-type displacements (Ishihara 1993).

Where alluvial soils and land fills have failed during more recent damaging earthquakes, e.g. Loma Prieta (1989), detailed studies and quantification of geotechnical phenomena and processes have been possible. Water losses in a sediment volume following liquefaction causes settlement of the ground surface. However, flow-type failures and lateral spreading are also causes of ground level reduction. Whilst the rate of settlement varies with the magnitude and distribution of vertical and horizontal permeabilities, the extent of settlement is proportional to the initial density and the maximum shear strain during shaking (De Sitter 1964, Tokimatsu & Seed 1987, Ishihara & Yoshimine 1991). Estimates of post-liquefaction volumetric strain, and hence settlements, can be made when the factors of safety (for failure) and relative density of each layer of the soil

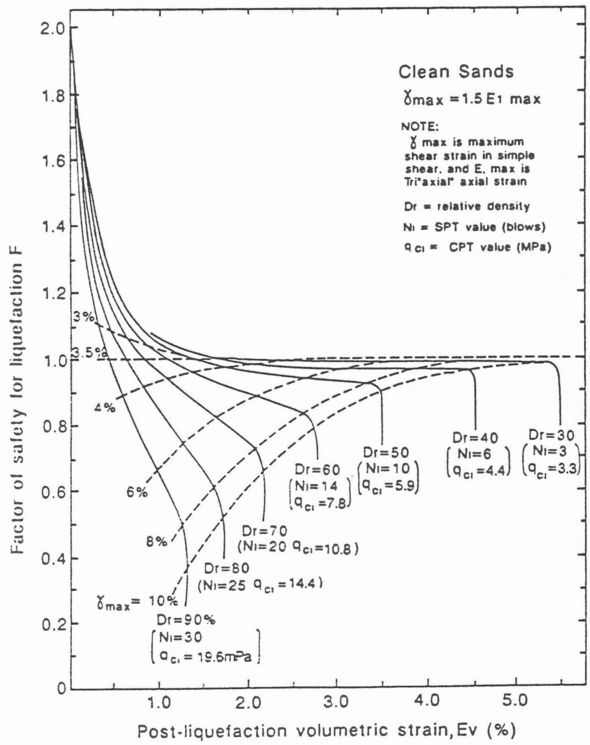

Fig. 3. Chart for determination of the post-liquefaction volumetric strain as a function of factor of safety (after Ishihara 1993).

profile are known. The use of standard penetration test (SPT) and cone penetration test (CPT) data for estimating relative densities is well documented (Seed et al. 1983) and has been critically reviewed many times, most recently by Ishihara (1993). Factors of safety, with their attributed SPT blow counts (N_1-values) or CPT tip resistance (q_{c1}-values) can be used to derive estimates of post-liquefaction volumetric strain (Ev%) from relationships such as those shown in Fig. 3. In this case the total settlement at the ground surface is the sum of the vertical settlement increments estimated from the Ev-values of each layer.

Such methods are valid for level ground situations, but when slopes, albeit slight, are involved then additional initial and dynamic shear stresses must be considered. In the case of gently sloping ground, and also for dikes and buildings with low dead weights, the effects of the initial sustained shear stress on the triggering of liquefaction has been considered to be negligible (Ishihara 1993). However, ground water conditions and soil fabrics must influence such considerations. More detailed combined field and experimental studies are required to increase data bases and refine understanding of the processes leading to post-liquefaction flow-type failures in low-angle mixed deposits. Earthquake geotechnicians and geologists should reappraise the many known cases of failure caused by earthquakes in the light of results of research carried out during the past decade in Japan and the USA.

Hazard evaluation perspectives

The total description of ground response during a damaging earthquake can only be achieved by the integration of surficial, depth and areal components of a full data base containing all relevant geological, geotechnical and seismological properties of the local (site specific) natural materials. Whilst geomorphologists and geotechnical engineers have tended to focus on surface features, earthquake engineers and soil dynamicists have concentrated on subsurface aspects. The areal 'big picture', both actual and scenario, has become increasingly within the domain of specialists concerned with planning regulation, codes, and geological hazard assessment. Attempts to bring all the disciplines and objectives together to provide complete descriptions of earthquake risk on urban, regional and global scales in earthquake-prone areas are gathering momentum, particularly in developing regions, e.g. the Global Seismic Hazard Assessment Program (GSHAP) (Giardini & Basham 1993). Increasing awareness of earthquake hazard assessment, reduction, advice and insurance should create opportunities for the application of new approaches and research directions beyond the siting and design methodologies of past decades.

Three ground response evaluation 'tools' have moved to the front of earthquake engineering geology:

(i) *Intensity scaling* using local and general classifications of the responses of built structures, and both natural and artificial ground deposits.

(ii) *In situ measurement* of key geotechnical properties (intrinsic, static and dynamic) affecting vulnerability to amplified motions and failure.

(iii) *Palaeoseismology* which provides new information on (large) prehistoric earthquakes by utilizing geological and geotechnical insights gained from the study of palaeoliquefaction and surface displacements.

Some aspects of current thinking and developments in these three domains are discussed below.

Table 2. Terrestrial terrain earthquake vulnerability chart for intensity scaling.

Conditions	Materials	Examples	Shearwave velocity (ms^{-1})	Scaling factor (MSK 1993)
Class I Bedrock	a Massive, foliated strong rocks	Plutonic rocks; lavas	1400–2000	0 –0.3
	b Horizontally bedded and foliated strong rocks	Basement sedimentary rocks	900–1400	0.3–0.8
	c Dipping and folded strong and weak rocks	Schists, slates, limestones and sandstones	700– 900	0.8–1.2
Class II Cover Rock	a As 1b with thick weak beds	Sandstone shale sequences	600– 700	1.2–1.5
	b As 1c with thick weak beds and local intensive fractures	As IIa with local severe shearing	450– 600	1.5–1.8
	c Mainly highly weathered rock and well consolidated sediments	Mudrocks, 'Rag and Hassock', old river terraces	300– 450	1.8–2.0
Class III Cover Deposit	a Interbeds of mainly consolidated clays and granular sediments lying on rock	Older alluvium, lake sediments and slope deposits	250– 300	2.0–2.5
	b Interbeds of poorly consolidated clay and sand lying on rock	Younger alluvium, etc	200 ±	3.0
	c As IIIb lying on thick weak sediments	Young coastal and fluvial deposits	200 ±	3.0
Class IV Made Ground	Artificial ground with possible poorly compacted fill materials	Embankment soils, land fills	100 ±	3.0

Intensity scaling classifications

Published relative intensity scales include those of Barosh (1969) and Evernden & Thomson (1985). Informed discussions of site effects and intensity-related issues are provided by Borcherdt (1975, 1985), Murphy & O'Brien (1977), Rogers et al. (1985) and Reiter (1990).

The methodologies and values cited in these works are used extensively in earthquake hazard scenarios and in the production of relative intensity maps. However, use in regions with geological conditions which differ from those of the data sources is problematic. The classification of Evernden & Thomson (1985) was created for geological conditions in the Los Angeles area of California, based upon surficial geological maps and the Rossi-Forel and Modified Mercalli intensity scales. Fumal & Tinsley (1985) found that their classification of near-surface geological materials for the Los Angeles area based on shearwave velocity data was rather different. Moreover, the California classification (Evernden & Thomson 1985) contains a relatively small number of categories, unlike the earlier scheme of Barosh (1969) which involves 26 terrain categories each with a large relative intensity range.

Such classifications can be modified to meet local needs in Europe. One scheme which could be considered for use in highly industrialised north-west European areas, such as the Netherlands and adjacent areas, is given in Table 2. As with other schemes, strong bedrock is given the zero (lowest) scaling factor because most published attenuation relationships used in Europe are based on bedrock strong motion data. Where bedrock is of less competent materials, shear wave characteristics need to be investigated to permit redefinition of the base scaling value for a local classification. The scheme given in Table 2 is considered to provide a sufficient number of terrain categories for flexible and general application. Each category is defined by a narrow range of shear-wave velocities and attributed with a narrow range of relative intensity values. For future 'global' seismic hazard mapping a uniform definitive absolute scale is likely to be used so that relative ground motion estimates can be compared

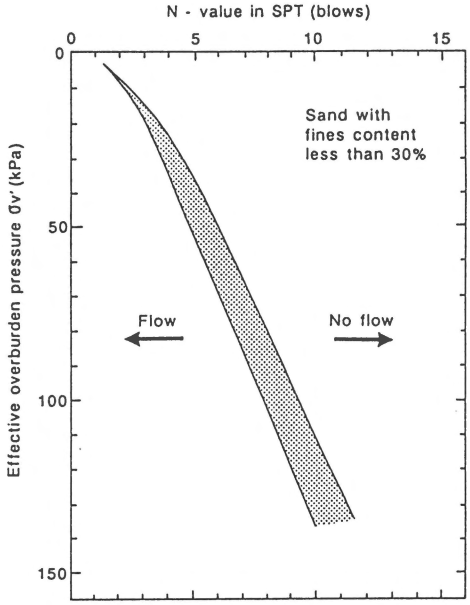

Fig. 4. Proposed boundary in Standard Penetration Test (SPT) N-value differentiating conditions of Flow and Non-Flow (after Ishihara 1993).

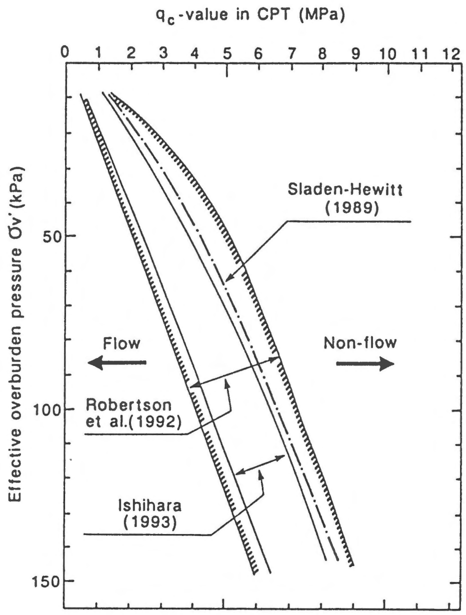

Fig. 5. Compiled boundaries in Cone Penetration Test (CPT) q_c-value separating Flow and Non-Flow (after Ishihara 1993).

worldwide. However, where feasible, new approaches to establishing local relationships between maximum ground motion parameters and ground response may be more rewarding (Margottini et al. 1992).

In situ geotechnical measurements

Fortunately, large-scale geophysical and geotechnical measurements, such as shear-wave velocities and penetration-resistances (SPT-CPT values), are becoming increasingly easy to carry out on local and even regional scales. Of particular relevance to studies of liquefaction potential and flow-type (landslide) failures in the Netherlands and adjacent areas are the results of recent research in Japan and California following unacceptably high damage levels to modern facilities in the 1980s. Of considerable interest are the analysis and interpretation of state-of-the-art SPT and CPT measurements which are not without controversy (Morris 1983, Seed 1985).

Ishihara (1993) has produced two boundary curves for SPT N-values and CPT q_c-values which separate levels of ground response and damage on the basis of Flow-NonFlow-Liquefaction domains (Figs 4, 5). Systematic mapping of areas of susceptible deposits throughout the Roer Valley graben zone using established and new SPT/CPT results should be considered in the near future with a view to producing liquefaction and flow slide hazard (GIS-type) maps. The Netherlands leads the world in SPT and CPT field measurement and interpretation, and, as evidenced by the sand injections at Herkenbosch and failures at the Brunssummerheide, certainly needs to assess ground vulnerability to earthquake shaking.

Palaeoseismology

Investigations into the geotechnical states of ground materials during and after strong motion are often carried out, particularly those which use relatively cheap methods of subsurface measurement, such as SPTs and dynamic cone tests. Unfortunately, at best, these data are no more than vertical scan lines of sediment bodies which may have experienced considerable changes in their internal geometry. Further insights into the strains and the geotechnical processes which take place during shaking and liquefaction can be provided by examination of the 'fossil' record of earthquakes, i.e. excavation of formerly susceptible sediments and kindred materials. Attributions of injection structures to strong ground motion, mainly sand dikes, have been on record for some time, e.g. New Madrid 1810–1811 (Saucier 1989), Charleston 1887 (Talwani & Cox 1985), and

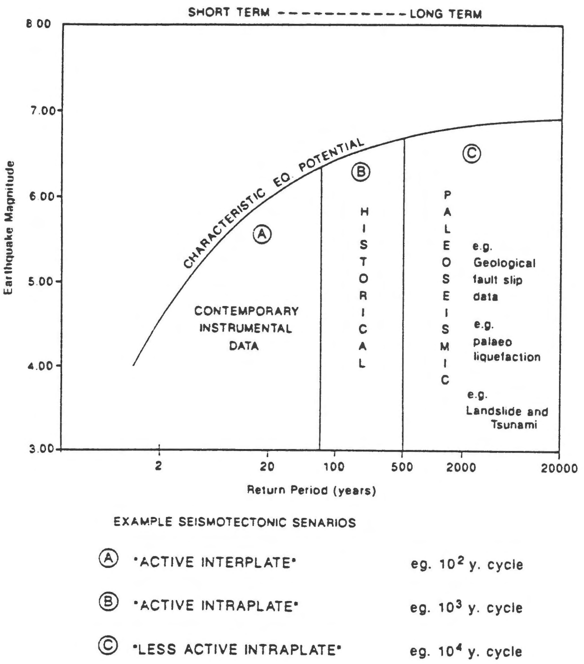

Fig. 6. Earthquake hazard component diagram (modified after Burton 1990).

more recently for Venezuela 1989 (Audemard & Santis 1991) and Japan-Kinai 1596 (Kanaori et al. 1993).

When such features are seen in sediments and in fracture zones, and can be proven by structural association, dating and/or geological correlation to be the consequence of earthquake shaking, they are called seismites (evidence for fossil seisms). Care is required in field investigation and interpretation, because many local seismic features may be created by non-seismite processes. However, seismite associations, when combined to form a palaeointensity map, should be unique and not attributable to any other known natural cause. Indeed, one might prefer to consider the whole event association, when proven, as a seismite.

Palaeoseismicity is a term which can be used to distinguish essentially geological information on earthquake activity from 'contemporary' (instrumental) and 'historical' (written) records (Wallace 1981, Davenport & Ringrose 1985, Allen 1986, Davenport 1993, Pantosti & Yeats 1993). Prehistoric surface displacements on seismogenic faults (Sieh 1984) and palaeoliquefaction (soft-sediment deformation) structures (Seilacher 1969, Davenport & Ringrose 1987) are the two main sources of evidence for palaeoseismicity. A comprehensive review of the literature on these phenomena is provided by Vittori et al. (1991). Trenching and erosion-feature enhancement using hand tools and large excavation equipment is normally required to expose fault traces and adjacent deformation features. It is important to realise that *in situ* evidence of coseismicity may require both types of information. Other evidence which has been used includes the periodic elevation of coastal features (Valensise & Pantosti 1992). Unfortunately, as with the application of attenuation relationships for strong motions, such local information has often not been acquired, is usually insufficient, or may never be available. Therefore, it is important to (a) be aware of what has been done elsewhere, is being done, and is transferable to north-west Europe; and (b) to encourage local studies to assemble the required databases. In parts of the world where active fault zones are capable of producing significant levels of earthquake activity, the assumption that much of the measured displacement at the surface is coseismic may be acceptable, but there are many areas for which such assumptions should not be made until firm seismotectonic associations can be established. Although most of the Roer and Rhine graben faults are seismogenic, evidence of strong shaking sufficient to cause collateral ground damage is still required to establish coseismicity. Where susceptible deposits are located, liquefaction and post-liquefaction dewatering could occur. Palaeoliquefaction phenomena should be sought in such terrains. To establish the size and location of a palaeoseismic event requires the use of a spectrum of diagnostic phenomena. There is a need to establish change of intensity level over a wide area within a traceable horizon. Evidence that such geological formations are contemporaneous should be strong and the spatial density of information should be adequate.

Although contemporary and ancient liquefaction phenomena and kindred mass movement structures have been reported from many 'more active' areas (e.g. Japan, Greece, Venezuela, Levant Rift, Red Sea, Iran, California, China, New Zealand), only in one case has a 'complete palaeoseismite' been described, namely in the Glen Roy area of Scotland (Ringrose 1989). During the past fifteen years the search for evidence of large earthquakes in intraplate areas has revealed evidence of palaeoliquefaction, surface rupture and landslides in the formerly glaciated areas of Scandinavia and Canada, as well as Scotland (Mörner et al. 1988, Adams 1989, Muir Wood 1989). These areas have special geological attributes, i.e. they are areas of hard crystalline rock which have been extensively scoured by ice and

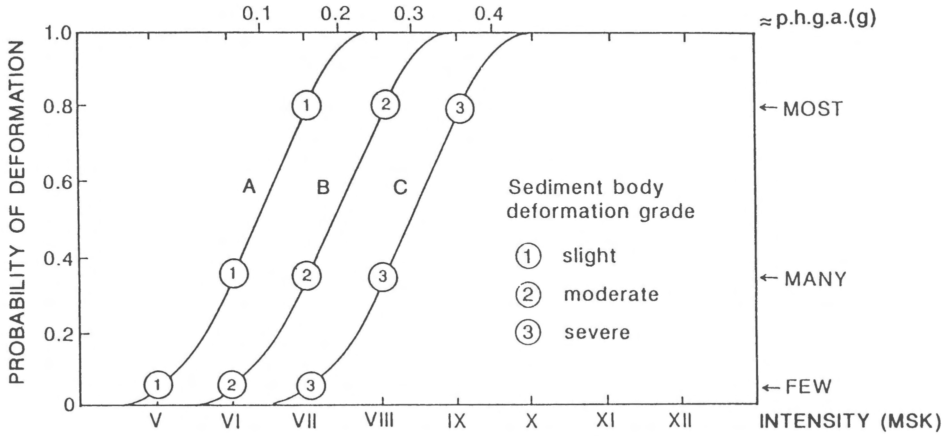

Fig. 7. Hypothetical soft-sediment vulnerability to earthquake shaking for three types of sediment body (A, B and C). p.h.g.a. = peak horizontal ground acceleration.

then mantled in places by glacial debris and meltwater lakes. When isostatic adjustment follows ice retreat there is evidence of rock fracture and earthquake activity (Jacobs & LaFountain 1975, Mörner & Adams 1989, Gregersen & Basham 1989). The earthquakes appear to be much larger in the past (late- and post-glacial times) and are 'fossilised' in susceptible deposits such as glacial lake sediments. Glacial lake sediments are made up of fine sand to silt sized grains of rock 'flour' and therefore behave as sandy silts. At Glen Roy a horizon within a 10 300 to 10 700 yrBP sequence of sediments liquefied and dewatered during a shallow earthquake close to a local ice-front. Landslides were triggered (and reactivated) over an area of 80 km^2, liquefaction damage in the form of soft-sediment deformation structures occurred to distances of up to 14 km from an ancient reactivated surface fault trace, and a small surface displacement on the fault occurred along a length of some 7 km. Based upon comparison of the total evidence with appropriate empirical relationships (Kuribayashi & Tatsuoka 1975, Ambraseys & Melville 1982, Bullen & Bolt 1985, Keefer 1984), the size of the event is estimated to be circa M = 6.25–6.5 and the depth only a few kilometres (Davenport et al. 1989).

Because palaeoseismicity is essentially the fossil record of earthquake activity it must play its part in hazard analyses (Burton 1990). The contributions made will vary with the hazard methodology. There are a number of approaches which can be called 'short-term' hazard assessment; these have the aim of giving estimates based upon essentially instrumentally-derived earthquake catalogue values of earthquake size and frequency. In many regions of the world these approaches are the basis of earthquake codes for design and construction of ordinary built structures. The requirements and formulation of regulations for the siting and design of special engineered structures, particularly dams, power plants and nuclear facilities, have focussed increasing attention upon the so-called 'long term' hazard assessment methodologies. These require the use of records over longer periods of time because of the greater importance of information on the largest earthquakes. In strictly scientific terms it can be argued that the division into short- and long-term assessments is unreal. Both are 'segments' of the total hazard concept which can be thought of as the quantification of the seismic cycle for a given region (P.W. Burton pers. comm.). This requires a near complete data set of a duration spanning several cycles and including the greatest (maximum) earthquake. Seismic cycles vary in length between tectonic regions and zones. A schematic relationship between seismic cycles, 'types' of earthquake record and maximum earthquake potential of a region is shown in Fig. 6.

In terms of the general conditions for liquefaction, nearfield strong ground motions favour rapid loss of shear strength at some depth in a loose sediment body, followed by rapid migration of water and concomitant deformation and destruction of layers. When uniform sand layers with some degree of initial compaction are subject to such motions, they may initially dilate and, in doing so, will become 'brittle' and fracture. Assuming a given sediment fabric and type, a suite of 'strain

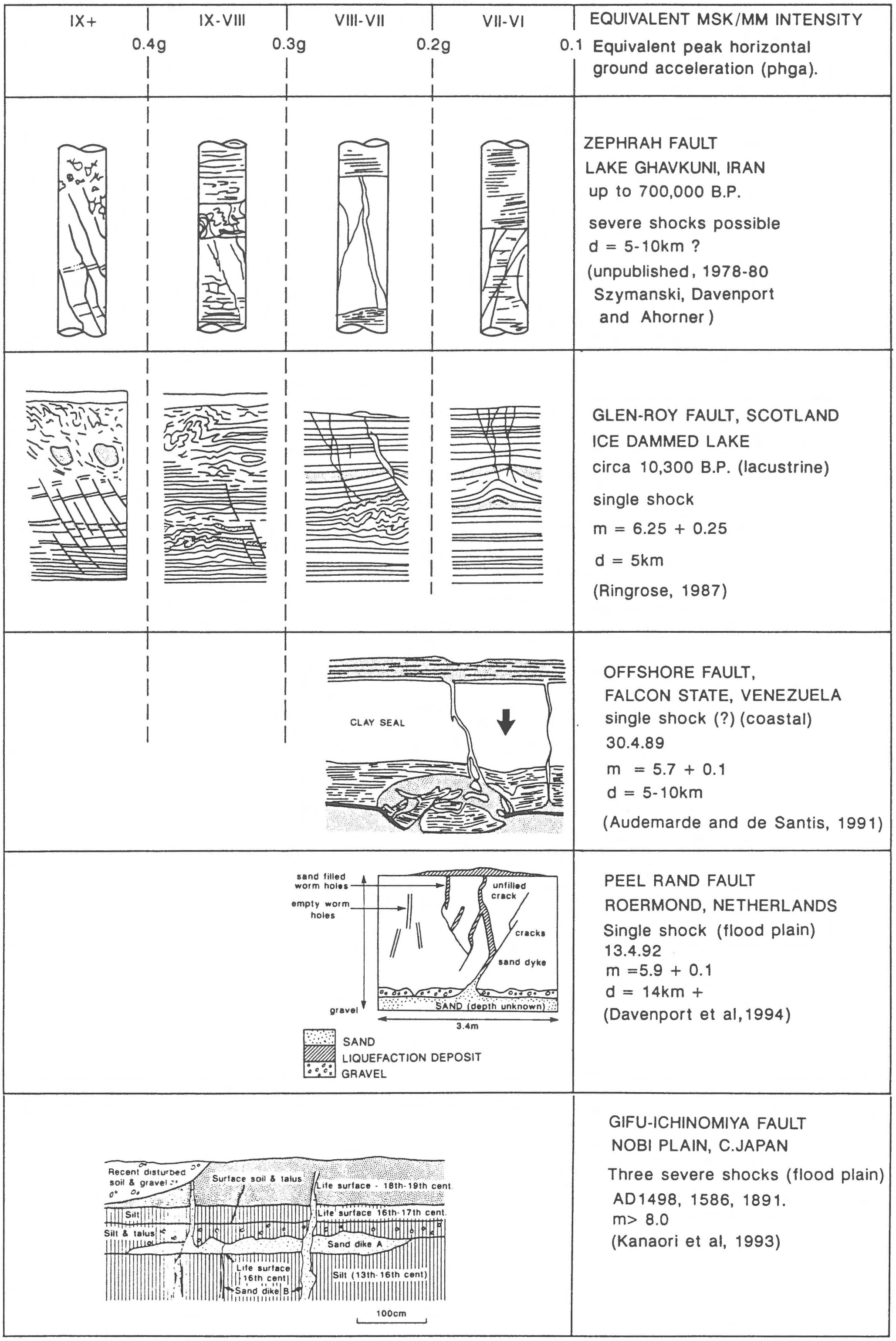

Fig. 8. Example palaeoliquefaction strain patterns and their estimated strongmotion regimes. m = earthquake magnitude, d = hypocentral depth.

states' within sand-silt sequences may be recognisable, with the greatest intensities of ground motion being recorded by fault-graded structures and well developed ball-and-pillows. Lesser intensities would be recorded by partial ball-and-pillow structures, confined layer disruption, and injections. Because non-seismic soft sediment deformation and syn- and post-liquefaction deformation both exhibit similar structural features (often due to dewatering processes), it is important, where possible, to consider the diagnostic features as functions of soft-sediment vulnerability (Fig. 7).

In the few examples of palaeoliquefaction which are well documented, only one data set is known to be sufficiently complete to permit confident interpretation as a palaeoseismite and the quantification of the possible size and depth of the causative earthquake, i.e. Glen Roy in Scotland. However, similar phenomena have been noted elsewhere and comparisons can be made, e.g. Iran (Szymanski et al. 1979), Venezuela (Audemard & de Santis 1991), France (Fourniguet et al. 1993) and the Netherlands (Davenport et al. 1994). Where sufficient liquefaction phenomena are available they can be ranked by degrees of 'palaeointensity of deformation', as shown in Fig. 8. With sufficient field exposures, these classes can be used to produce a unique areal pattern which can be interpreted as a palaeointensity map. When the location of the source fault is known, correlation with published empirical relationships between earthquake size (shallow) and limits-of-liquefaction distances can be used to estimate the size of the event (Fig. 9). Although field evidence of liquefaction is accumulating, the number of reliable observations is still meagre (Peck 1979, Davis & Berrill 1983, Davenport 1993).

Should age-dating and sedimentology permit, a record of a sequence of prehistoric earthquakes may be compiled (Davenport et al. 1989). The facing direction of a half-set of palaeoisoseismals would indicate the direction of location of the causative fault. Palaeoisoseismal spacing could provide a basis for estimates of earthquake depth, and elongation of the higher intensity isoseismals may indicate the trend and location of a surface fault trace and the extent of near-field strong motions. Most importantly, for hazard assessments, the extreme-value probabilistic methodology can be constrained in the very long return period domain, i.e. a range of magnitudes for very rare earthquakes which can be used to validate extreme values predicted by using Gumbel III statistics for regions for which only incomplete earthquake catalogues are available (Burton 1990).

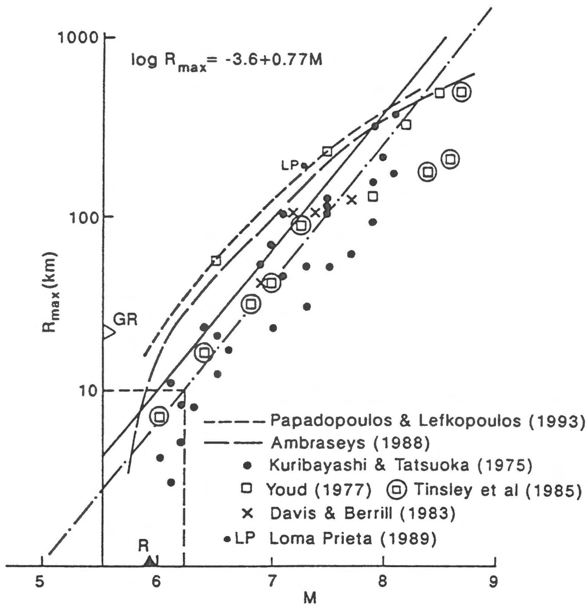

Fig. 9. Maximum distance to site of liquefaction versus earthquake magnitude (m). Formula and solid line after Kuribayashi & Tatsuoka (1975). Dashed-dot line fit after Tinsley et al. (1985). ▷ GR = Gleu Roy event, ▲R = Roermond earthquake.

Concluding remarks

The Roermond event of 1992 has provided a rare and timely opportunity to assemble world experience and consider which state-of-the-art issues need to be addressed in northwest Europe and the Rhine-Roer industrial areas. Geotechnical and strong motion research has gained ground in recent decades. However, the syn- and post-liquefaction behaviour of cohesionless deposits, so common in the Netherlands and adjacent areas, is onl y just beginning to be quantified to a level sufficient to permit use in rigorous large-strain potential (settlement, flow) and hazard assessment. The most important information, and often the most difficult to quantify accurately, is that which derives from field investigations, particularly immediate post-seismic microzoning and excavation. Inspired by the frequency of occurrence of young faults and damaging earthquakes in the Rhine-Limburg areas (see Ahorner 1983) and encouraged by Prof. David G. Price of the Engineering Geology Section at TU Delft, Joris Lap carried out his now-famous study of earthquake-induced liquefaction potential in the more-earthquake-prone areas of the Netherlands (Lap 1987). Not only were the levels of liquefaction for a postulated M = 6 earthquake on the Peel Boundary Fault south of

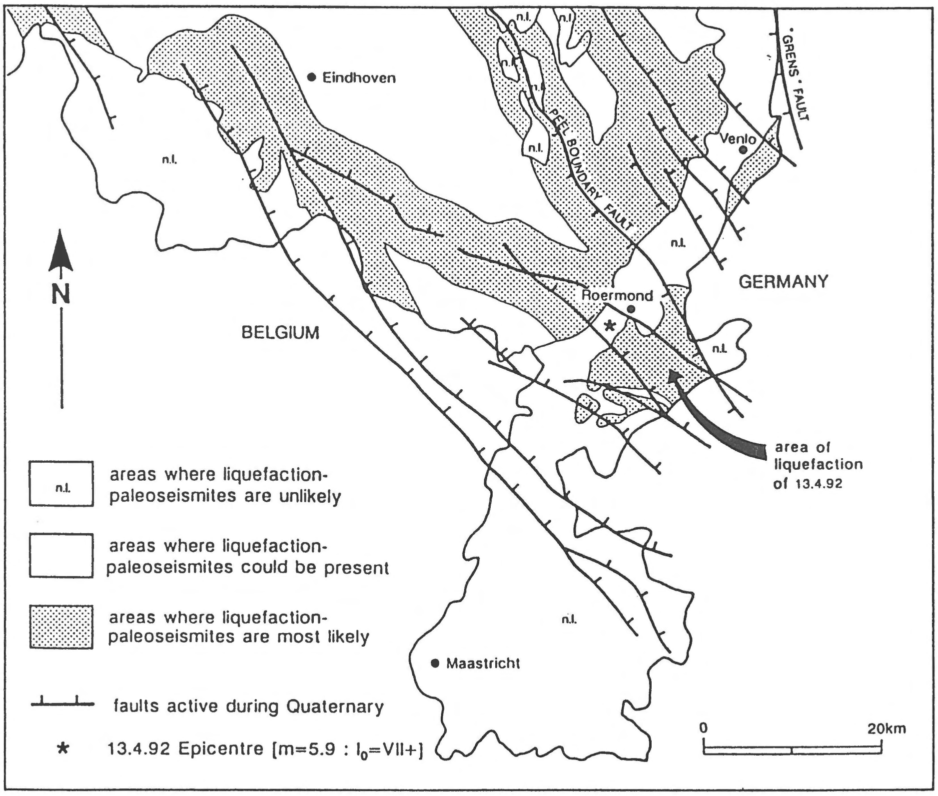

Fig. 10. Palaeoliquefaction opportunity map of Quaternary deposits in the southern Netherlands (based on Lap 1987).

Roermond anticipated, but the wider implications for earthquake hazard assessment were considered. Having mapped areas and estimated levels of liquefaction susceptibility and opportunity, Lap proposed that, in certain areas close to seismogenic surface faults, vulnerable deposits should be investigated for evidence of palaeoliquefaction (Fig. 10).

The above issues are recommended to be carried out as a priority in any future hazard assessment research in the region. Included in such studies should be:

- validation of the occurrence of palaeoliquefaction records in suitable geological situations,
- excavation and mapping of sediments and fault traces for age dating and analysis,
- drilling of fault zones and CPT/SPT profiling at selected sites,
- assembling a database containing geological and geotechnical observations.

Care must be taken when interpreting soft-sediment deformation structures as seismites. In the Netherlands and elsewhere, similar morphologies and sediment associations show clear evidence of glacio-tectonic and cryogenic processes (Croot 1988). However, palaeoseismites have associations which enable them to be distinguished from glacially-controlled phenomena, provided sufficient areally-widespread contemporaneous observations can be recorded. The first-order features which distinguish palaeoliquefaction are (a) the presence of a laterally-extensive contemporaneous disrupted layer of a susceptible deposit beneath a sequence of layers which are only disturbed by water-flow and dewatering effects, and (b) areal intensity-type zoning of deformation styles over a restricted area independent of contemporary water depth, sediment facies and climatic indicators. Such palaeoseismic data are essential if the longer-term components of seismic hazard are to be incorporated into contemporary state-of-the-art hazard assessments, for example, Burton (1990), De Crook (1993), McGuire (1993), Muir-Wood (1993) and Davenport (1993).

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References

Adams, J. 1989 Postglacial faulting in eastern Canada: nature, origin and seismic hazard implications – Tectonophysics 163: 323–331

Ahorner, L. 1983 Seismicity and neotectonic structural activity of the Rhine graben system in central Europe. In: A.R. Ritsema & A. Gürpinar (eds.): Seismicity and seismic risk in the offshore North Sea area – Reidel, Dordrecht: 101–111

Ahorner, L. 1993. Erfahrungen aus dem Erdbeben bei Roermond am 13. April 1992 – Schweizerische Pool für Erdbeben-versicherung – 14 Geschäftsbericht, Bern: 10–26

Alkema, D., M. Mosselman & I. Paulussen 1994 Earthquake-triggered landslides at the Brunssummerheide, Limburg, the Netherlands: Preliminary studies following the 1992 Roermond earthquake – Geol. Mijnbouw, this issue

Allen, C.R. 1986 Seismological and palaeoseismological techniques of research in active tectonics. In: R.E. Wallace (ed.): Active Tectonics – National Acad. Press: 148–154

Ambraseys, N.N. 1988 Engineering seismology: first Mallet-Milne lecture – Earthq. Eng. Struct. Dyn. 17: 1–105

Ambraseys, N.N. & J.J. Bommer 1991 The attenuation of ground accelerations in Europe – Earthq. Eng. Struct. Dyn. 20: 1179–1202

Ambraseys, N.N. & C.P. Melville 1982 A history of Persian earthquakes – Cambridge Univ. Press, 219 pp

Audemard, F.A. & F. de Santis 1991 Survey of liquefaction structures induced by recent moderate earthquakes – Bull. Int. Ass. Eng. Geol. 44: 5–16

Barosh, P.J. 1969 Use of seismic intensity data to predict the effects of earthquakes and underground nuclear explosions in various geological settings – US Geol. Surv. Bull. 1279: 93 pp

Basham, P.W. & D. Giardini 1993 Technical guidelines for global seismic hazard assessment: Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36 (3–4): 15–24

Bonilla, M.G., R.K. Mark & J.J. Lienkaemper 1984 Statistical relations among earthquake magnitude, surface rupture length and surface fault displacement – Bull. Seismol. Soc. Am. 74: 2379–2411

Boore, D.M. & N.N. Ambraseys 1993 Some notes concerning prediction of ground motions. In: D. Giardini & P.W. Basham (eds.): Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36 (3–4): 169–180

Borcherdt, R.D. (ed.) 1975 Studies for seismic zonation of the San Francisco Bay region – U.S. Geol. Surv. Prof. Paper 941-A: 52–67: 88–96

Borcherdt, R.D. 1985 Predicting earthquake ground motion: an introduction – U.S. Geol. Surv. Prof. Paper 1360: 93–99

Boswell, P.G.H. 1961 Muddy sediments: some geotechnical studies for geologists, engineers and soil scientists – W. Heffer & Sons Ltd., Cambridge: 140 pp

Bullen, K.E. & B.A. Bolt 1985 An introduction to the theory of seismology, 4th ed – Cambridge Univ. Press, Ch 17: pp 432–469

Burton, P.W. 1990 Pathways to seismic hazard evaluation: extreme and characteristic earthquakes in areas of low and high seismicity – Natural Hazards 1: 275–291

Campbell, K.W. 1981 Near-source attenuation of peak horizontal acceleration – Bull. Seismol. Soc. Am. 71: 2039–2070

Coburn, A. & R. Spence 1992 Earthquake protection – John Wiley: 355 pp

Cotecchia, V. 1986 Ground displacement and slope instability triggered off by the earthquake of November 23, 1980, in Campania and Basilicata, Proc. Int. Sym. Eng. Geol: Problems in seismic areas: Int. Ass. Eng. Geol. – Bari, Italy (4): 1915–1940

Cotecchia, V. 1987 Earthquake-prone environments. In: M.G. Anderson & K.S. Richards (eds): Slope stability – John Wiley: 287–330

Coulter, H.W. & R.R. Migliaccio 1966 Effects of the earthquake of March 27, 1964, at Valdez, Alaska – US Geol. Surv. Prof. Paper 542-C: 1–36

Croot, D.G. (ed.) 1988 Glaciotectonics: forms and processes – Balkema: 212 pp

Das, B.M. 1983 Fundamentals of soil dynamics – Elsevier: 399 pp

Davenport, C.A. 1993 Palaeoseismicity: hazard impact and research needs – Global Seismic Hazard Assessment Program (GSHAP) Regional Meeting, Nairobi: 9 pp

Davenport, C. & P. Ringrose 1985 Fault activity and palaeoseismicity during Quaternary time in Scotland – preliminary studies. In: Earthquake Engineering in Britain – T. Telford: 81–93

Davenport, C.A. & P.S. Ringrose 1987 Deformation of Scottish Quaternary sediment sequences by strong earthquake motions. In: M.E. Jones & R.M.F. Preston (eds.): Deformation of sediments and sedimentary rocks – Geol. Soc. London, Blackwell: 299–314

Davenport, C.A., P.S. Ringrose, A. Becker, P. Hancock & C. Fenton 1989 Geological investigations of late and post glacial earthquake activity in Scotland. In: S. Gregersen & P.W. Basham (eds.): Earthquakes at North-Atlantic passive margins: Neotectonics and Post-glacial Rebound – Kluwer: 175–194

Davenport, C.A., J.M.J. Lap, P.M. Maurenbrecher & D.G. Price 1994 Liquefaction potential and dewatering injection structures at Herkenbosch: Field investigations of the effects of the Roermond 1992 earthquake, the Netherlands – Geol. Mijnbouw, this issue

Davis, R.O. & J.B. Berrill 1983 Comparison of liquefaction theory with field observations – Géotechnique 33: 455–460

Davis, S.N. & J. Karzulovic 1963 Landslides at Lago Rinihue, Chile – Bull. Seismol. Soc. Am. 53 (6): 1403–1414

Dawson, A.G., D. Long & D.E. Smith 1988 The Storegga Slides: evidence from eastern Scotland for a possible tsunami – Mar. Geol. 82: 271–276

De Crook, Th. 1993 Probabilistic seismic hazard assessment for The Netherlands – Geol. Mijnbouw 72: 1–13

De Sitter, L.U. 1964 Structural geology – McGraw-Hill, 2nd ed. 551 pp

Donovan, N.C. 1973 A statistical evaluation of strong motion data including the February 9, 1971, San Fernando earthquake. Proc. 5th World Conf. Earth. Eng. – Rome 1: 1252–1261

Evernden, J.F. & J.M. Thomson 1985 Predicting seismic intensities – US Geol. Surv. Prof. Paper 1360: 151–202

Fourniguet, J. et al. 1993 La Paléoséismicité ou 'A la recherche des séismes perdus' – Géochronique 46: 15–22

Fuller, M.L. 1912 The New Madrid earthquake – US Geol. Surv. Bull. 494: 119 pp

Fumal, T.E. & J.C. Tinsley 1985 Mapping shear-wave velocities of near surface geologic materials – US Geol. Surv. Prof. Paper 1360: 127–149

Giardini, D. & P.W. Basham 1993 Technical guidelines for seismic hazard assessment: Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36 (4): 15–24

Gregersen, S. & P.W. Basham (eds.) 1989 Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound – NATO ASI Series C Vol 266, Kluwer: 716 pp

Gürpinar, A. 1977 A stable attenuation law based on RMS of strong motion acceleration. Proc. Symp. Analysis of Seismicity and on Seismic Risk – Liblice: 209–217

Hadley, J.B. 1964 Landslides and related phenomena accompanying the Hebgen Lake earthquake of August 17, 1959 – US Geol. Surv. Prof. Paper 435: 107–138

Hansen, W.R. 1965 Effects of the earthquake of March 27, 1964, at Anchorage, Alaska – US Geol. Surv. Prof. Paper 542-A: 1–68

Hasegawa, H.S. & H. Kanamori 1987 Source mechanism of the magnitude 7.2 Grand Banks earthquake of November 1929: double couple or submarine slide? – Bull. Seismol. Soc. Am. 77: 1984–2004

Hays, W.W. 1980 Procedures for estimating earthquake ground motions – US Geol. Surv. Prof. Paper 1114: 77 pp

Heezen, B.C. & M. Ewing 1952 Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake – Am. J. Science 250: 849–873

Howard, T.R. (ed.) 1983 Seismic design of embankments and caverns – Am. Soc. Civil. Eng. Geotech. Eng. Div. Spec. Pub.: 201 pp

Idriss, I.M. 1978 Characteristics of earthquake ground motions – J. Geotech. Eng. Div. ASCE 3: 1151–1265

Ishihara, K. 1985 Stability of natural deposits during earthquakes – Proc. 11th Int. Conf. Soil Mech., San Francisco 1: 321–376

Ishihara, K. 1993 Liquefaction and flow failure during earthquakes – Géotechnique 43 (3): 351–415

Ishihara, K. & M. Yoshimine 1991 Evaluation of settlements in sand deposits following liquefaction during earthquakes – Soils Foundations 32 (1): 173–188

Jacobs, A.M. & L.J. LaFountain 1975 Seismicity and glacial rebound in the central stable region – Geol. Soc. Am. Abs. with Programs 7 (7): 1129–1130

Joyner, W.B. & D.M. Boore 1981 Peak horizontal acceleration and velocity from strong motion records, including records from the 1979 Imperial Valley, California, earthquake – Bull. Seismol. Soc. Am. 71: 2011–2038

Joyner, W.B. & T.E. Fumal 1985 Predictive mapping of earthquake ground motion. In: J.I. Ziony (ed.): Evaluating earthquake hazards in the Los Angeles region – an earth science perspective – US Geol. Surv. Prof. Paper 1360: 203–220

Kanaori, Y., S-I. Kawakami, K. Yairi & T. Hattori 1993 Liquefaction and flowage at archeological sites in the inner belt of central Japan: Tectonic and hazard implications – Eng. Geol. 35: 65–80

Keefer, D.K. 1984 Landslides caused by earthquakes – Geol. Soc. Am. Bull. 95: 406–421

Krinitzsky, E.L. & F.K. Chang 1988 Intensity-related earthquake ground motions – Bull. Ass. Eng. Geol. 4: 425–435

Kuribayashi, E. & F. Tatsuoka 1975 Brief review of liquefaction during earthquakes in Japan – Japan Soils & Found. 15 (4): 82–92

Lap, J.M.J. 1987 Earthquake-induced liquefaction potential in the area south of Eindhoven, the Netherlands – Mem. Centre Eng. Geol. Netherlands 47 (1, 2): 40 pp

Lee, I.K., W. White & O.G. Ingles 1983 Geotechnical engineering – Pitman: 508 pp

Lindenberg, J., E.O.F. Calle & A.C.W.M. Vrouwenvelder 1994 Safety of dikes and embankments in the Netherlands with special reference to earthquakes – Geol. Mijnbouw, this issue

Maurenbrecher, P.M., D.G. Price & W. Verwaal 1994 Technical note on the 1992 Brunssummerheide landslide in Limburg, the Netherlands – Geol. Mijnbouw, this issue

Margottini, C., D. Molin & L. Serva 1992 Intensity versus ground motion: a new approach using Italian data – Eng. Geol. 33: 45–58

McCulloch, D.S. & M.G. Bonilla 1967 Railroad damage in the Alaskan earthquake – Am. Soc. Civil Eng., J. Soil Mech. Found. Div. 93 (1): 89–100

McCulloch, D.S. & M.G. Bonilla 1970 Effects of the earthquake of March 27, 1964, on the Alaska railroad – US Geol. Surv. Prof. Paper 545-D: 161 pp

McGuire, R.K. 1993 Computations of seismic hazard. In: D. Giardini & P.W. Basham (eds.): Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36 (3–4): 181–200

Milne, W.G. 1977 Seismic risk map for Canada – Sixth World Conf. on Earthquake Engineering, Delhi 2: 508

Mörner, N-A., C.A. Davenport, P.S. Ringrose, H. Henkel & H. Agrell 1988 Present Processes and Properties in the Lithosphere (PPPL) – Report on Neotectonics, Stockholm: 98 pp

Mörner, N-A. & J. Adams (eds.) 1989 Paleoseismicity and Neotectonics – Tectonophysics 163: 340 pp

Morris, D.V. 1981 A note on earthquake-induced liquefaction – Géotechnique 33: 451–454

Muir Wood, R. 1989 Extraordinary deglaciation reverse faulting in northern Fennoscandia. In: S. Gregersen & P.W. Basham (eds.): Earthquakes at North-Atlantic Passive Margins – Kluwer: 141–173

Muir Wood, R. 1993 From global seismotectonics to global seismic hazard. In: D. Giardini & P.W. Basham (eds.): Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36 (3–4): 153–168

Murphy, J.R. & L.J. O'Brien 1977 The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters – Bull. Seismol. Soc. Am. 67: 877–915

Nieuwenhuis, J.D. 1994 Liquefaction and the 1992 Roermond earthquake, the Netherlands – Geol. Mijnbouw, this issue

Nuttli, O.W. 1974 Seismic wave attenuation and magnitude relations for eastern North America – J. Geophys. Res. 78: 876–885

Okamoto, S. 1973 Introduction to Earthquake Engineering, University of Tokyo Press, Earthpressure during earthquakes – Ch 9: 209–254

Oldham, R.D. 1899 Report on the great earthquake of 12 June 1897 – Mem. Geol. Surv. India, 29: 1–379

Pantosti, D. & R. Yeats 1993 The paleoseismicity of the late Holocene. In: D. Giardini & P.W. Basham (eds.): Global Seismic Hazard Assessment Program (GSHAP) Technical Planning Volume – Annali di Geofisica 36: 237–257

Papadopoulos, G.A. & G. Lefkopoulos 1993 Magnitude-distance relations for liquefaction in soil from earthquakes – Bull. Seism. Soc. Am. 83: 925–938

Peck, R.B. 1979 Liquefaction potential: science versus practice – J. Geotech. Eng. Div. Am. Soc. Civil Eng. 105 (3): 393
Plafker, G. & G.E. Ericksen 1978 Navados Huascaran avalanches, Peru. In: B. Voight (ed.): Rockslides and avalanches, 1 – Natural Phenomena, Elsevier: 277–314
Prior, D.B. & J.M. Coleman 1978 Disintegrating, retrogressive landslides on very low angle subaqueous slopes, Mississippi Delta – Marine Geotech. 2: 37–60
Radbruch-Hall, D.H. & D.J. Varnes, 1976 Landslides, cause and effect – Bull. Inst. Ass. Eng. Geol. 14: 205–216
Reiter, L. 1990 Earthquake hazard analysis – issues and insights – Columbia Univ. Press: 254 pp
Richter, C.F. 1958 Elementary seismology – W.H. Freeman: 768 pp
Ringrose, P.S. 1989 Palaeoseismic (?) liquefaction events in lake sediments at Glen Roy, Scotland – Terra Nova 1: 57–62
Robertson, P.K., D.J. Woeller & W.D.L. Finn 1992 Seismic cone penetration test for evaluating liquefaction potential under cyclic loading – Can. Geotech. J. 29 (3): 686–695
Rogers, A.M., J.C. Tinsley & R.D. Borcherdt 1985 Predicting relative ground response. In: J.I. Ziony (ed.): Evaluating earthquake hazards in the Los Angeles region – an earth science perspective – US Geol. Surv. Prof. Paper 1360: 221–247
Rosenblueth, E. 1986 The Mexican earthquake: a first hand report – Civil Eng., Jan: 38–40
Saucier, R.T. 1989 Evidence for episodic sand-blow activity during the 1811–1812 New Madrid (Missouri) earthquake series – Geology 19: 103–106
Seed, H.B. 1968 Landslides during earthquake due to soil liquefaction – Am. Soc. Civil Eng. 94: 1053–1122
Seed, H.B. 1970 Soil problems and soil behaviour. In: R.L. Wiegel (ed.): Earthquake engineering – Prentice-Hall: 227–251
Seed, H.B. 1979 Considerations in the earthquake-resistant design of earth and rockfill dams – Géotechnique 29: 215–263
Seed, H.B. 1983 Earthquake-resistant design of earth dams. In: T.R. Howard (ed.): Seismic Design of Embankments and Caverns – Am. Soc. Civil Eng. (Spec. Publ.): 41–64
Seed, H.B. 1985 Discussion of Morris (1983) – Géotechnique 35: 369–370
Seed, H.B. & I.M. Idriss 1967 Analysis of soil liquefaction, Niigata earthquake – J. Soil Mech. Found. Div., Am. Soc. Civil Eng. 93 (3): 83
Seed, H.B. & I.M. Idriss 1982 Ground motions and soil liquefaction during earthquakes – Earthq. Eng. Res. Inst.: 210 pp
Seed, H.B., K.L. Lee & I.M. Idriss 1969 Analysis of Sheffield Dam failure. J. Soil Mech. Found. Div., Am. Soc. Civil Eng. 95 (6): 1453–1490
Seed, H.B., I.M. Idriss & L. Arango 1983 Evaluation of liquefaction potential using field performance data – Am. Soc. Civil Eng.: J. Geotech. Eng. 109 (3): 458–482
Seilacher, A. 1969 Fault-graded beds interpreted as seismites -- Sedimentology 13: 155–159
Serva, L. 1994 The effects of the ground in the Intensity Scales – Terra Nova, in press
Sieh, K.E. 1984 Lateral offsets and revised dates of large prehistoric earthquakes at Pallett Creek, southern California – J. Geophys. Res. 89: 7641–7670
Sims, J. 1975 Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments – Tectonophysics 29: 141–152
Sladen, J.A. & K.J. Hewitt 1989 Influence of placement method on the *in situ* density of hydraulic sand fills – Can. Geotech. J. 26: 453–466
Slemmons, D.B. 1977 State of the art for assessing fault hazards in the United States, Rep. 6: faults and earthquake magnitude – US Army Corps Eng., Waterways Exp. Station, Vicksburg, Misc. Pap. S-73-1: 129 pp
Spudich, P. & J. Orcutt 1982 Estimation of earthquake ground motion relevant to the triggering of marine mass movements. In: S. Saxov & J.K. Nieuwenhuis (eds.): Marine slides and other mass movements – Plenum: 219–231
Szymanski, J.S., C.A. Davenport & L. Ahorner 1979 Evaluations of palaeoseismicity – Lake Ghavkuni, Iran – unpublished reports to the Atomic Energy Commission of Iran
Talwani, P. & J. Cox 1985 Palaeoseismic evidence for recurrence of earthquakes near Charleston, South Carolina – Science 229: 379–381
Taylor, C.L. & L.S. Cluff 1977 Fault displacement and ground deformation associated with surface faulting. In: The current state of knowledge of Lifeline Earthquake Engineering – Spec. Publ. Am. Soc. Civil Eng.: 338–353
Terzaghi, K. & R.B. Peck 1967 Soil mechanics in engineering practice, 2nd ed – Wiley International: 729 pp
Tinsley, J.C. & T.E. Fumal 1985 Mapping Quaternary sedimentary deposits for areal variations in shaking response. In: J.I. Ziony (ed.): Evaluating earthquake hazards in the Los Angeles region – an earth science perspective – US Geol. Surv. Prof. Paper 1360: 101–126
Tinsley, J.C., T.L. Youd, D.M. Perkins & A.T.F. Chen 1985 Evaluating liquefaction potential. In: J.I. Ziony (ed.): Evaluating earthquake hazards in the Los Angeles region – an earth science perspective – US Geol. Surv. Prof. Paper 1360: 263–316
Tokimatsu, K. & H.B. Seed 1987 Evaluation of settlements in sands due to earthquake shaking – Am. Soc. Civil. Eng.: J. Geotech. Eng. Div. 113: 861–878
Trifunac, M.D. & A.G. Brady 1975 On the correlation of seismic intensity with peaks of recorded strong ground motion – Bull. Seismol. Soc. Am. 65: 139–162
Valensise, G. & D. Pantosti 1992 A 125 Kyr-long geological record of seismic source repeatability: the Messina Straits (southern Italy) and the 1908 earthquake (Ms $7^1/_2$) – Terra Nova 4: 472–483
Vittori, E., S.S. Labini & L. Serva 1991 Palaeoseismology: review of the state of the art – Tectonophysics 193: 9–32
Wallace, R.E. 1981 Active faults, paleoseismology and earthquake hazards in the western United States. In: D.W. Simpson & T.G. Richards (eds.): Earthquake prediction: an international review – Am. Geophys. Union, Washington DC, Maurice Ewing Ser. 4: 209–216
Wilson, R.C. & D.K. Keefer 1983 Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, earthquake – Bull. Seismol. Soc. Am. 73: 863–877
Wilson, R.C. & D.K. Keefer 1985 Predicting areal limits of earthquake-induced landsliding. In: J.I. Ziony (ed.): Evaluating earthquake hazards in the Los Angeles region – an earth science perspective – US Geol. Surv. Prof. Paper 1360: 317–346
Yeats, R.S., M. Clark, E.A. Keller & T.K. Rockwell 1981 Active fault hazard in southern California: ground rupture vs. seismic shaking – Bull. Geol. Soc. Am. 92 (1): 189–196
Youd, T.L. 1971 Landsliding in the vicinity of Van Norman Lakes. In: The San Fernando, California, Earthquake of February 9, 1971 – US Geol. Surv. Prof. Paper 733: 105–109
Youd, T.L. 1977 Discussion of 'Brief review of liquefaction during earthquakes in Japan' by Kuribayashi and Tatsuoka – Soil Found. 17 (1): 82–85