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SEISMIC GEOTECHNICAL CONSIDERATIONS - AN OVERVIEW

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ABSTRACT

This paper reviews seismic geotechnical considerations with respect to ground motion, ground failures and current practice. First, it discusses the influence of the seismic source, wave transmission and local site effects on the ground motion input. Secondly, it reviews various types of earthquake-induced ground failures including: liquefaction and lateral spreading, landslides, rockfalls, sinkholes, slope slumps and deformations, and fault displacements. The potential for the development of any one of the above-mentioned ground failures at a given site needs to be identified. This potential risk is either to be avoided by not using the site, or to be controlled by adopting various mitigative measures to reduce its impact on structures. Finally, the paper presents some observations relative to geotechnical earthquake engineering practice.

KEYWORDS

Ground motion; ground failures; geotechnical

INTRODUCTION

Ground and foundations affect the seismic performance of structures in two ways. First, they influence the ground motion imparted to the super-structure. Secondly, they carry both the static and dynamic loadings from the super-structure during the earthquake shaking. Thus, satisfactory seismic performance of buildings and lifeline structures depends not only on sound design of the structure itself, but also on relevant geotechnical conditions and soil-structure interaction. This paper presents an overview of geotechnical considerations for seismic structural design.

GROUND MOTION

Physical factors affecting the actual ground motion imparted to a structure include: the seismic source, wave transmission from source to site, local site effects and soil-structure interaction. However, the design of the structure is governed by the perceived seismic risk as reflected by the design earthquake adopted by the building codes and design guidelines applicable to the specific location of the structure. Some of the important considerations related to ground motion are outlined in this section.

Under-estimation of Ground Motion

Significant under-estimation of the design earthquake motion caused by erroneous judgement on any of the above-mentioned factors or by failure to implement correct assessments is an open invitation to major damage, especially for large earthquakes occurring in heavily developed areas. Thus, with hindsight, some recent earthquakes can be cited as examples of under-estimation of ground motion: the 1976 Tangshan Earthquake (relics of liquefaction due to earlier earthquakes identified only during post-earthquake investigations), the 1985 Michoacan Earthquake (soft soil amplification effect underestimated although its importance was recognized much earlier such as in the 1967 Caracus earthquake) and the 1995 Kobe Earthquake (the ruptured fault and the potential magnitudes of earthquakes associated with the fault were known to the geologists long before the earthquake).

Heaton (1995) pointed out that our collective experience with the seismic structural performance to date may not be sufficient to ascertain their capacity to survive ground motions with large displacements and/or long durations. Heaton and Allen (1995) also pointed out that blind thrust faults, whose fault planes do not extend to the ground surface, may evade detection by geologists. However, micro-geomorphology and integration of data from seismology, geology and geodesy (including the Global Positioning System) have been used to overcome this difficulty.

Bolt (1995) cited an initiative in California to improve earthquake-resistant design by installing "Reference Accelerometer Stations" in the vicinity of all clusters of significant structures. This initiative will increase the database of recordings, both in the free-field and within structures, for future correlations between building damage and seismic incident waves by means of detailed dynamic analyses.

Seismic Source

Schwartz (1988) reviewed source characterization as the basis for evaluating the seismic potential for a site. Within the epicentral region, details of the earthquake rupturing mechanism (magnitude and direction of fault displacement) and its propagation direction (uni-direction or bi-direction and towards or away from the site) exerts great influence on the characteristics of ground motion. The 1989 Loma-Prieta earthquake of magnitude 6.9 showed that the bi-directional fault rupturing process took only 7 to 10 secs, about half of the time for earthquakes of similar magnitude ruptured uni-directionally. Amplitudes of accelerations experienced in the epicentral region tend to be high. Values approaching or exceeding gravitational acceleration have been recorded or inferred in many instances. Furthermore, amplitudes of the vertical acceleration tend to be on par with horizontal accelerations, for earthquakes involving significant fault displacements in the dip direction such as thrust faults. The assumption of the vertical acceleration values being about two-thirds of the corresponding horizontal values could under-estimate the vertical acceleration in the near field. This could have significance in evaluating the structural design against vertical load including uplift. For strike-slip faulting earthquakes the ground motion could contribute significantly to torsional loading of structures in the epicentral area, as observed in the 1976 Tangshan earthquake in China.

Bolt (1995) emphasized the importance of relatively long-duration, energetic (mainly polarized SH wave) pulses present in many strong motion recordings in the near field of large earthquake sources related to the rapid rebound of the fault and to the directivity of the moving fault rupture. He referred to this wave feature as the source "fling", which has significant influence on non-linear structural behaviour. He cautioned against the fallacy of adopting scaled strong-motion accelerograms as seismic design motions based only on the values of peak ground acceleration (normally from waves of 6 to 10 Hz frequency range) without due consideration of the source "fling".

Wave Transmission and Local Effect

These two effects are discussed together because they are closely related. Wave transmission from the source to the structure site involves a complex process in a three-dimensional domain. The amplitudes, frequency content and duration of seismic waves undergo substantial modification through this process, which has received considerable attention in seismological research (Joyner and Boore 1988, Aki 1988, and Finn 1991). Outlined in the following are significant observations related to these effects.

Distance Attenuation Generally, ground motion attenuates less with distance for earthquakes involving more extensive source zones, i.e., large-magnitude earthquakes and/or subduction earthquakes (Crouse et al. 1988). In North America, ground motion attenuates less with distance in the east than in the west due to the difference in physical properties of the crust. Locally, ground motion attenuates less with distance in the direction parallel to the strike of a causative fault than normal to the strike. Thus, it is important to consider these factors when one evaluates seismic risk for a specific site, especially in areas where the existing database is rather sparse and projection based on databases obtained from elsewhere may be required.

Seismic Wave Coherency Ground motion time histories differ in wave form at various points located sequentially due to wave emission delays at the fault rupture and wave scattering along transmission paths. For long-span structures with multiple supports, this lack of coherency of ground motion (phase shift) between support points becomes a relevant design consideration. Bolt (1991) reviewed this aspect and evaluated its effect using records from the SMART 1 accelerograph array in Taiwan. Reduction of the dynamic response of support points up to 25 % was computed at 5 Hz for spans of 200 m.

Soil Amplification and Higher Modes When the natural period of a site coincides with that of a structure, pseudo-resonance will occur and greatly increase the seismic excitation of the structure. This phenomenon is responsible for significant damage to or collapse of tall structures with long period founded on deep deposits of soft soils. Substantial seismic amplification occurs where large contrast of the impedances (shear stiffness) of near surface materials exists (Romo and Seed 1987). For soft clays of high plasticity, the 1985 Michoacan and 1989 Loma Prieta earthquakes showed that their elastic response extends to relatively large shear strain levels. Hence, the acceleration range over which soil amplification may occur in soft clay sites has been raised from 0.1 g to 0.4 g (Idriss 1990).

The authors suspect that pseudo-resonance in higher modes might have contributed to the midheight storey collapse of some buildings in Mexico City during the 1985 Michoacan Earthquake and in Kobe City during the 1995 Hyogo-Ken Nanbu Earthquake. Storage of heavy materials in midheight storeys has been attributed as the contributing factor for such a collapse in Mexico City, while other structural defects have been postulated as the reason in Kobe City. However, in both instances, deep soft soil deposits were involved, and higher-modes of site response have been recorded. The natural site periods of the first three modes were inferred to be 2, 0.7 and 0.3 seconds at SCT site in Mexico City (Resendiz and Roesset 1987) and 2.4, 0.9 and 0.3 seconds in Kobe City (CAEE 1995). In a ground motion study for the Fraser Delta in British Columbia, the authors computed natural periods for several sites involving deep deltaic deposits of relatively low shear wave velocities (Sy et al. 1991). The calculated periods for the first three modes are, respectively, in the following ranges: 1.8 to 3.3 sec, 1.1 to 1.5 sec and 0.6 to 1 sec. Thus, higher modes of site response should be considered in structural design on deep, soft soil sites.

Aki (1988) and Silva (1989) reviewed the two-dimensional effects of seismic waves in sediment basins with different shape factors (ranging from shallow and wide to deep and narrow). The sediment - basement rock interface generates surface waves and may trap body waves in the sediments. Results from two-dimensional analyses could differ from those by one-dimensional analyses in the response amplitude, natural frequency and duration, depending on the shape factor of the basin and site location.

Standing surface waves could form under special circumstances where boundary conditions are conducive to such a development. Wang (1981) computed wave lengths of such standing waves that developed in the

Duohe valley across a river bend during the Tangshan earthquake and offered an explanation to the fact why a row of five single-story hospital buildings of similar design and construction suffered different fates. Two survived the earthquake, while the other three collapsed. The alternating building-failure pattern also coincided with the observed pattern of sandboils.

It is quite natural to suspect that surface wave amplification due to focusing, reflection and refraction phenomena could also contribute to the concentration of heavily damaged buildings in clusters within sediment basins. However, positive identification of the linkage between the wave and damage patterns in more complicated geometries and subsurface profiles is a much more difficult task.

Topographic Amplification Silva and Darragh (1989) showed that over the period range of engineering interest, 0.04 to 5 sec, the range of surface wave lengths is from 40 m to 5 km (assuming a shear wave velocity of 1 km/s). Topographical features with characteristic dimensions in this range have the potential for significant site amplification. In general, broad-band amplification occurs at the crest, while interference of waves cause more complex patterns of frequency-dependent amplification along the slope. The three-dimensional effect and ridge to ridge interaction could further accentuate the topographic effect.

Soil-Structure Interaction

In addition to the site amplification effect discussed above, both kinematic and inertial soil-structure interactions could further alter the translational, torsional and rocking modes of structural responses (Resendiz and Roesset 1987 and Finn and Ventura 1994). Factors influencing these interactions include: type and geometry of the foundation, relative rigidity of the structure, foundation and subsoil, and frequency and velocity of seismic waves. The evaluation of this effect requires detailed analysis based on good databases of ground and structure strong motion records.

GROUND FAILURES

This section reviews various types of earthquake-induced ground failures including: liquefaction and lateral spreading, landslides, rockfalls, sinkholes, slope slumps and deformations, and fault displacements. The potential for the development of any one of the above-mentioned ground failures at a given site needs to be identified. This potential risk is either to be avoided by not using the site, or to be controlled by adopting various mitigative measures to reduce its impact on structures.

Liquefaction and Lateral Spreading

Ground failures involving liquefaction, including flow slide and lateral spreading, have been responsible for extensive damage and failure of structures and lifeline facilities, especially in areas near water fronts where saturated soils are subjected to static shear loading. NRC (1985) provided a comprehensive review of this phenomenon. Recent findings on the evaluation of liquefaction for silty soils were reviewed by Finn et al. (1994), and that for gravelly soils were presented by Sy et al. (1995).

Existing geotechnical investigation methods for evaluating the susceptibility of cohesionless soils to liquefaction such as the dynamic Standard Penetration Test (SPT) and Becker Penetration Test (BPT) (BPT tests for materials with higher gravel and cobble content) and the static Cone Penetration Test (CPT) are reliable and cost-effective. Other methods such as shear-wave and geophysical measurements are also cost-effective means to obtain additional relevant information for seismic evaluation.

Empirical correlations have been established for estimating both the seismically-induced deformations (Bartlett and Youd 1995) and the relationship between ground deformation and structural damage (Youd 1989). In addition, the failure mode involving liquefaction or flow slide is an important concern for man-made structures such as earthfill and tailings dams, dykes and embankments. Failures of these earthfill structures tend to occur in older or improperly designed ones. Because of the potential release of stored fluids and/or semi-solids retained by the structures in the event of such a failure, many of these structures are being retrofitted to increase their resistance to earthquakes.

In general, cohesionless deposits of coral origin have larger void ratios than their siliceous counterparts, Mejia and Yeung (1995) indicated that conventional liquefaction investigation procedures and criteria using the SPT data might also be applied to coralline soils, based on their investigation of liquefaction-affected sites in Guam after the 1993 magnitude 8.1 earthquake. Similar investigations on coralline soils in future could improve our understanding on their seismic performance.

Landslides, Rockfalls, Sinkholes, Slope Slumps and Deformations

Earthquakes trigger landslides and rockfalls in natural and man-made slopes whose margin of safety against sliding is reduced by inertial loading, and/or reduction of material shear strength due to straining or pore pressure increase. Ishihara (1985) used several case histories involving natural slopes to illustrate the importance of geological and groundwater factors in defining the failure mechanism of landslides and the increase of "apparent" cohesion in partially-saturated plastic clayey soil under seismic loading.

Earthquakes also cause the formation of sinkholes where the surficial soil layer collapses into existing underground voids created by abandoned mine workings, (e.g., in coal mines during the 1976 Tangshan earthquake, NAS 1980) or developed due to internal erosion by seepage (e.g., in Matahina Dam during the 1987 Edgecumbe magnitude 6.3 earthquake in New Zealand, Gillon 1988).

A potentially costly problem is related to the less severe earthquake-induced deformations of hillside fills. Due to the pressure of urban sprawl, many hill slopes have been developed for residential, commercial and industrial usages. Stewart et al. (1995) reviewed the problem of damage to housing developments in the Los Angles area during the 1994 Northridge earthquake, and emphasized the need for better control of land use and development to mitigate the problem. Reported characteristic fill deformations include cracking at cut/fill contacts, lateral extension, settlement in fill and bulging of slope surfaces near the one-third point of the slope height.

Fault Displacements

For shallow earthquakes, fault displacements in the epicentral region often rupture the ground surface and cause damage to structures other than that associated with strong shaking. Thus, fault displacements in highly developed areas and in areas crossed by linear lifeline facilities, such as transportation routes, tunnels, pipelines and communication and power lines, are important design considerations (TCLEE 1995). Wang and O'Rourke (1977) discussed some of the measures used to mitigate damage to buried lifelines.

GEOTECHNICAL OBSERVATIONS

Mitchell et al. (1995) reviewed 30 case histories involving the performance of improved ground during recent earthquakes in U.S.A. and Japan. They indicated that available ground improvement methods such as chemical and compaction grouting, jet grouting, soil mixing, vibro-compaction, vibro-replacement, compaction piles, and dynamic compaction, etc. are effective in providing protection against ground failure and in limiting seismic deformations.

Quality control and assurance programs are essential for the successful application of ground improvement methods. A recent test program involving densification by compaction grouting reported gradual reduction of strength gain after the treatment. However, this apparent strength reduction may be due to the gradual relaxation of lateral effective stresses in the ground, which in turn may be influenced by the limited areal extent of treatment in the testing program (Mejia and Boulanger 1995). When insitu blasting is used for densifying cohesionless soils, the gradual strength gain with time should be monitored and confirmed (Narin van Court and Mitchell 1995).

Foundation failures in Mexico City during the 1985 Michoacan earthquake are reviewed by Marsal (1987) and Girault (1987). Spread footings with no reinforced tie-beams were responsible for poor performance of low-rise (two- to three-storey) buildings. Failures and or excessive settlements of pile and mat foundations involved insufficient bearing capacity and resistance to overturning moments. While these foundation failures may be related to unusual subsoil conditions in Mexico City, they do provide valuable lessons for foundation engineering in difficult soft soils.

Zelinski et al. (1995) reviewed bridge foundation remediation considerations including: lateral force and ductility demands, foundation flexibility and pile survivability based on the experience of California Department of Transportation. They indicated the importance of providing sufficient tensile as well as compressive load capacity and a trend toward using larger-diameter, thicker-section and more ductile pile systems to meet current design requirements. Due to the increase of demands on foundation systems on one hand and the utilization of less competent soil sites on the other, they pointed out the need for closer interaction among structural, geotechnical and construction engineers in order to arrive at a sound and cost-effective design.

SUMMARY

This paper reviews seismic geotechnical considerations with respect to ground motion, ground failures and current practice. It illustrates the importance of many physical factors controlling the seismic ground motion input. As more strong motion recordings become available, we will continue to learn the influence of these factors on the generation and propagation of seismic waves. With detailed post-earthquake investigations and analyses after each major earthquake, our ability to correlate the performance of both the ground and structures with the seismic input will improve. Experience to date shows that current geotechnical investigations, procedures for analysis and ground improvement techniques are effective. Further contributions from geotechnical engineers to earthquake-resistant design will come from a closer working relation with structural engineers as seismic structural design progresses from the force-based to displacement-based criteria.

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