13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 573

EVALUATION OF FAULT RUPTURE HAZARD IN THE BUILT URBAN ENVIRONMENT

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SUMMARY

Surface fault rupture during an earthquake can be a serious and dangerous hazard to people and structures, especially if built over a fault. Surface fault rupture has been observed to create differential offsets of up to several tens of meters. As it is not possible to design structures to accommodate the differential ground movements associated with fault rupture, it is imperative to identify the precise locations of potential fault rupture surfaces to properly site new structures away from faults and to evaluate the potential hazards to existing structures that may be located over the fault traces. In a rural environment, there may be surficial or topographic evidence indicative of the location of past fault ruptures. However, in an existing urban environment, such clues to past ruptures may be totally obliterated due to changes in the landforms and the presence of construction. The most direct method of identifying surface fault rupture hazard is to excavate trenches across the general trend of the suspected fault trace and visually identify stratigraphic discontinuities that may indicate a seismogenic origin. In an urban built environment, there may not be sufficient space to excavate trenches to allow for direct observation. Where trenching is not possible, geologists are now using a large array of different subsurface exploration techniques. These techniques include using combinations of high resolution geophysical surveys, closely spaced continuous core borings, large-diameter borings allowing downhole logging by a geologist, and cone penetration test soundings. Although the latter subsurface exploration techniques may only provide discrete data, detailed evaluation and correlations between explorations may disclose discontinuities indicating the presence of potential fault rupture surfaces. These combined techniques have been used successfully in identifying the presence or absence of surface fault rupture hazard.

INTRODUCTION

Surface fault rupture has been recognized as one of the seismic hazards that is most difficult, if not impossible, to mitigate against, other than complete avoidance. Structures constructed over active faults that have historically ruptured have been severely damaged or destroyed due to the differential movement of the ground when the fault ruptures.

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An example of damage and destruction due to surface fault rupture in a recent earthquake in Taiwan is shown in Figure 1. After surface fault rupture and other seismic hazards caused extensive damage during the February 9, 1971 San Fernando earthquake in the Los Angeles, California area, the State of California enacted a law known currently as the Alquist-Priolo Earthquake Fault Zone Act. The State of California has given the responsibility of defining and identifying active faults (those with activity during the Holocene age or within the last 11,000 years) to the State Geologist and the California Geologic Survey (Hart[1]). This Act is intended to protect public safety by requiring disclosure during any real estate transfers or transactions if the property in question is within a designated Earthquake Fault Zone. The Act also requires that projects for development must investigate the potential for surface fault rupture and, if evidence of recent fault activity is found, to set back any building developments from the active fault traces. In a sense, the Alquist-Priolo Earthquake Fault Zone Act is a good example of land-use management. Out of its requirements, projects in California that are within State-designated Earthquake Fault Zones must be investigated to assure that buildings for human habitation (more than 2000 person-hours per year) are not constructed over an active fault trace. If faulting is suspected, a determination of the relative age of the lowermost unfaulted materials is required to evaluate the recency of faulting. In California, evidence must exist to demonstrate that the lowermost unfaulted material are Pleistocene age (greater than 11,000 years) or older, to prove that the fault is not to be considered “active.” The base of the Holocene age (11,000 years before present) materials must be evaluated to determine if active faults exist that would present a potential surface rupture hazard. The standard of practice in California is generally to set back a minimum of 15 meters from the closest active fault trace. This paper will discuss the various methods of investigation for evidence of prior fault rupture, with particular emphasis to the problems posed by the built urban environment.

Figure 1. Surface fault rupture through a middle school (Taiwan, 1999)

The method of exploration required to perform a fault rupture hazard investigation will depend on several factors, including site access, depth of Holocene deposits, the presence of diagnostic strata underlying the ground surface, the physical properties of the strata (i.e., ability to stand vertically in an open trench excavation), the presence of shallow ground water, as well as other factors.

The most common and typical exploration method used for a fault rupture hazard investigation is trenching (see Figure 2). Trenching is the most desirable (and cost-effective) method to investigate the presence or absence of faulting because of the direct visual observation and correlation of the stratigraphic units it allows.

Figure 2. Typical Trench Excavation

In many densely urbanized areas (such as Los Angeles, see Figure 3) trenching is commonly not a feasible option because of the large working area required and the expected thickness (often greater than 30 feet or about 9 meters) of relatively young sediments. If trenching were to be attempted in urban areas with a thick sequence of Holocene age sediments, a large area would be needed and it is likely that extensive and costly shoring would be required to be able to investigate to the required depths. In addition, several municipalities require site investigations to extend a minimum distance (typically 50 feet or about 15 meters) beyond the building limits. In densely urban environments (where property is a premium and space is limited), this requirement would entail investigating either across adjacent properties and/or into the public right-of-ways. Trenching is not typically a feasible option beyond the site boundaries. Also, trenching would be of limited use where there are deep fill soils mantling the natural soils or if there is shallow ground water.

Figure 3. Typical Densely Urbanized Area

Where trenching is not possible, geologists are now using a large array of different subsurface exploration techniques. These techniques include using combinations of closely spaced continuous core borings, cone penetration test soundings, high resolution geophysical surveys, and large-diameter borings allowing downhole logging by a geologist. These techniques used in combination have been successful in identifying the presence or absence of surface fault rupture hazards.

CONTINUOUS CORE BORINGS

Introduction

As an alternative to trenching, one method of performing fault hazard investigations consists of drilling a series of closely-spaced continuous-core hollow-stem-auger borings. The borings are drilled along transects oriented as close to perpendicular to the known trend of the fault in order to observe the maximum offset. Depending on the geologic environment, the lateral spacing between borings will vary. Typical initial boring spacing is on the order of 6 to 9 meters (20 to 30 feet, respectively); however, in areas where anomalies are observed between borings, the spacing is commonly reduced to 3 meters or less.

Methodology

Typically, the boring transects are drilled within the property limits, however, in densely developed areas, these borings are often drilled within the public right-of-way. Based on extensive experience, it has been found that the use of a CME dry-core method is quite successful. A 1.5 meter core barrel is fixed within the hollow-stem auger using hex-rod, which allows for oriented sampling. The sampler advances at the same rate as the outer auger cuts the annulus, thus obtaining a relatively undisturbed sample, even within unconsolidated alluvial deposits (see Figure 4).

Continuous sampling of the subsurface materials is performed with boring depths extending through the Holocene deposits into the Pleistocene materials. The recovered core materials are logged in fine detail as they are extruded from the borings, prior to removal from the core barrel. The color is included in the description and classification of the soils encountered based on the Munsell[2] color system. The core samples are logged for primary stratigraphy as well as observed for the presence of pedogenic soil horizons (buried soil horizons indicative of former ground surfaces). Detailed logging of the core samples and photographs of the recovered material within the core barrel is critical, especially when drilling in alluvial deposits.

Once the soil is removed from the sampler, fine stratigraphic details are commonly destroyed. The recovered core samples are placed in boxes for additional evaluation upon completion of the field investigation. At the termination depth, ground-water levels are allowed to stabilize and static water levels are measured in all of the borings. If necessary, piezometers are installed in the borings for future monitoring. In areas where geologic anomalies are observed between boring locations, it may be necessary to split the spacing between borings and drill supplemental borings.

The term soil refers to the pedogenic or weathering profile that develops into the ground surface. The use of soil horizons as markers is important as the soil represents a hiatus of sediment deposition. The degree of soil development is a function of several factors including climate, parent material, topography, and time exposed at the ground surface. Typically, older soil profiles exhibit a greater degree of soil development than younger soils. The ages of soils can be estimated based on comparisons to other described and dated soil chronosequences that have developed under similar climatic conditions and in similar parent materials.

The use of soil horizons as markers is important as the pedogenic soil will develop on the ground surface, regardless of the primary stratigraphy. These can be identified by organic-rich A horizon (or topsoil), underlain by an argillic horizon identified by the presence of secondary clay minerals within the primary matrix. Onlapping of stratigraphic units as well as lateral facies changes in primary stratigraphy are compensated as the pedogenic surface forms on the former ground surface. Age control is provided by radiometric age dating of detrital charcoal and comparison of color and secondary clay in other locally studied soils.

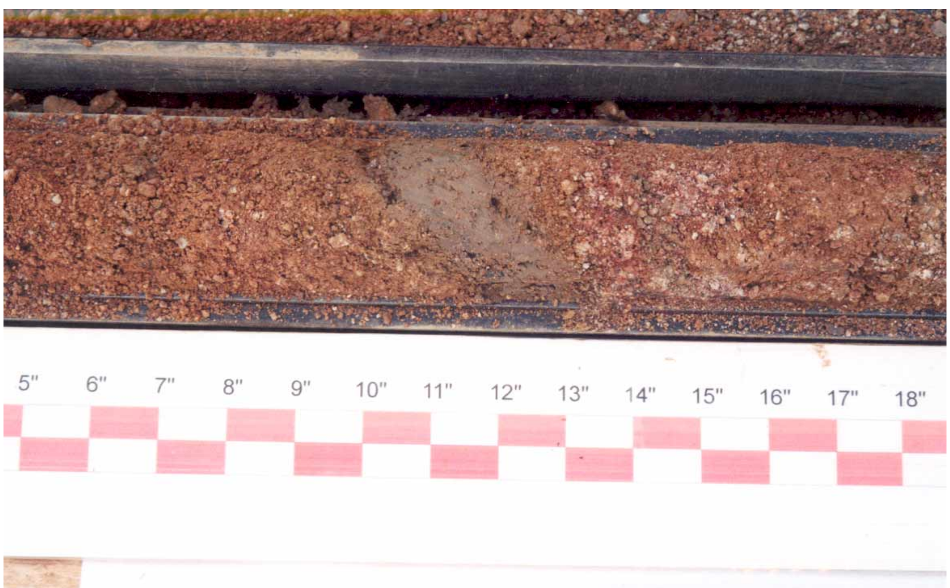

Figure 4. Recovered Core Sample

Analysis

Upon completion of the field investigation, the core samples from all of the borings are reviewed and evaluated in order to correlate the stratigraphy and soil profiles from boring to boring (see Figure 5). During this evaluation, a side-by-side comparison of the primary stratigraphy and secondary soil horizons is performed to develop a record of the subsurface stratigraphy and to correlate the materials between adjacent borings. The soils are correlated between adjacent borings on the basis of composition, color, texture, and the presence of any recognizable pedogenesis of the soils. This information is used to develop a detailed stratigraphic profile of the subsurface materials. Additionally, the recovered core samples are examined for presence of detrital charcoal and, if present, will be extracted for radiocarbon age dating if deemed necessary after logging and correlation of the soils.

Figure 5. Core Review and Correlation

The data from the borings and subsequent core logging and correlation is presented graphically in the form of a geologic cross section. The cross section includes a combination of the primary stratigraphy, secondary soil horizons, and ground-water levels to indicate locations of offsets. The interpretation of the geologic conditions can include descriptions of faulting, scoured channels, variable ground-water conditions, and truncated stratigraphy.

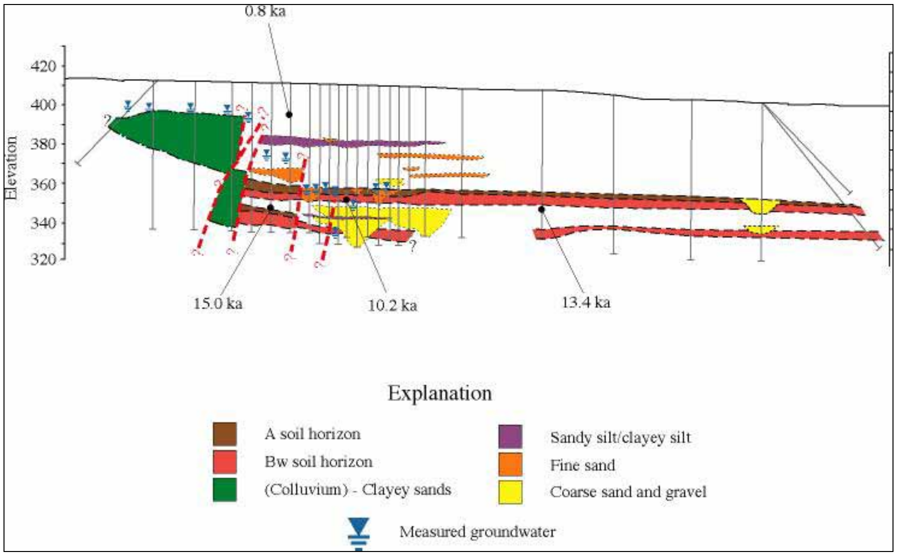

Figure 6. Interpreted Cross Section

CONE PENETRATION TESTING

Another alternative to trenching as a method of performing a fault rupture hazard investigation consists of performing a line of closely-spaced cone penetration tests, used in much the same way as a transect of continuous core borings. Cone penetration test (CPT) soundings can provide detailed stratigraphic correlations in shallow subsurface materials across a site. Closely-spaced CPTs can be used to verify the absence or presence of suspected fault traces identified in seismic reflection lines (described later), on aerial photographs, or other investigative tools. Exploratory borings need to be drilled adjacent to the CPT line, preferably between CPTs, to verify stratigraphic interpretation derived from CPT data and for the purpose of radiocarbon age-dating of soils. The CPTs are most useful where trenches are not feasible, either because of shallow ground water, caving soils, or a where a thick sequence of Holocene age materials are present and the Pleistocene age soils cannot be exposed.

CPTs can either be used as a secondary tool to further investigate suspected fault traces and other anomalies identified in geophysical surveys, topographic maps, aerial photographs, etc. or they can be used as a primary screening tool for identifying anomalies in the subsurface. If used as the primary screening tool, typical spacing could be farther apart to identify areas of anomalies. Then, more closely spaced CPTs can be performed to refine the stratigraphic section in the area of the identified anomaly.

Methodology

The cone penetration test consists of hydraulically pushing a cone at the end of a series of rods into the ground at a constant rate, continuously and simultaneously measuring the resistance and penetration of the cone. Measurements are also made of either the combined resistance to penetration of the cone and the outer sleeve surface or the resistance of the sleeve surface. During the advancement of the CPT, continuous measurements of cone bearing (Q_c), sleeve friction (F_s), and pore pressure (U) are recorded versus depth. The friction ratio (R_f) is calculated from Q_c and F_s. All these parameters are plotted versus depth.

Cone bearing, sleeve friction, and friction ratio (defined as the ratio of sleeve friction to cone bearing) can be related to common soil properties and soil classification. For example, increasing compressibility produces a decrease in the cone resistance with an increase in friction ratio (Robertson[3], Youd and Idriss[4]).

Stratigraphic Analyses

CPT data can provide detailed stratigraphic profiles; correlations between identified sediment layers (with similar electronic signatures) is possible within about 15 cm vertical increments. Detailed stratigraphic analysis of the CPT data can be used to identify sediment layers that are vertically very well-defined and laterally consistent between CPTs. Detailed lateral stratigraphic correlations between CPTs are typically based on identification of sediment layers with similar cone bearing, sleeve friction, and friction ratio signatures, in addition to similar soil type.

Seismic shear wave velocity testing of the subsurface can also be performed in the CPTs at intervals of 1 and 1.5 meters. The seismic velocity information from the CPTs was evaluated to estimate the dynamic soils properties in order to estimate dynamic stress and strain levels experienced at the site. The seismic velocity information can also be used during the geophysical survey to correlate between velocity and depth in the seismic profile. Additionally, pore water dissipation tests can be performed in the CPTs to identify the depth to ground water at the site.

Continuous-core borings are typically used in conjunction with the CPTs to confirm the results of the CPTs and to visually correlate the soils encountered in the boring to the results of the CPT.

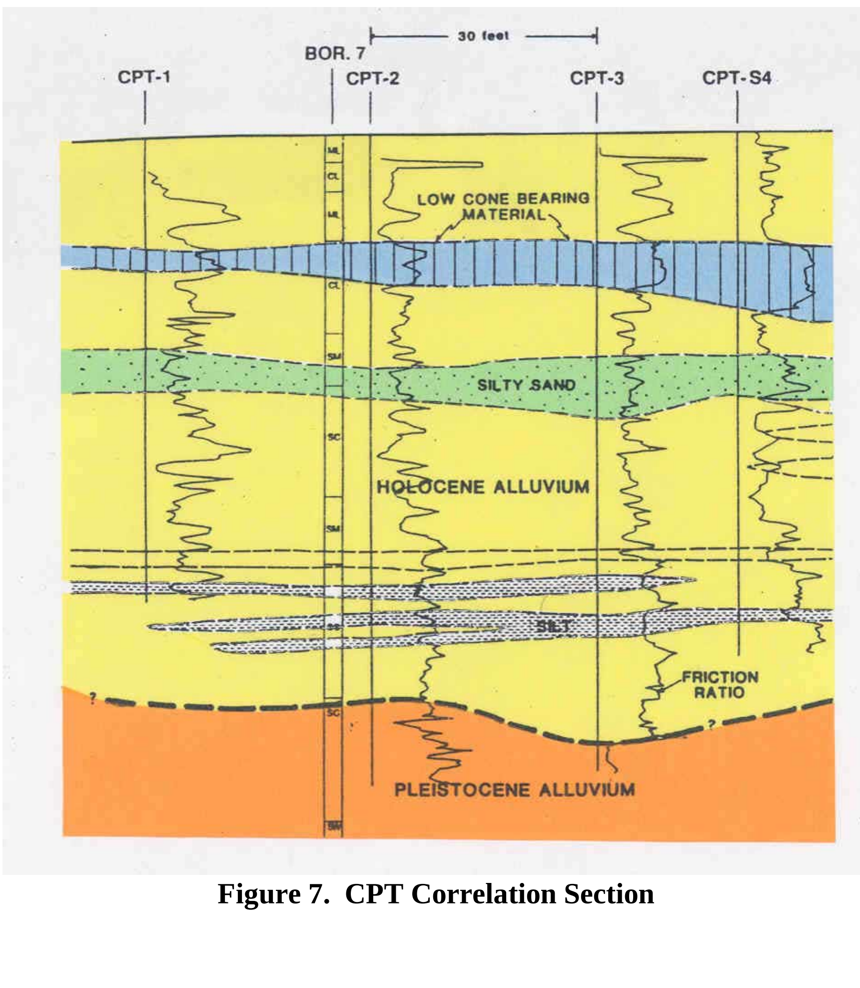

Figure 7. CPT Correlation Section

GEOPHYSICAL SURVEY

Introduction

Another method of evaluating the presence or absence of faults in dense urban environments is the use of a high-resolution seismic reflection survey (geophysical survey). A geophysical survey is a non-invasive process that images the subsurface stratigraphy at depth and provide a preliminary screening to identify the locations of potential faults. The high-resolution seismic reflection survey method uses closely spaced geophones (laterally spaced about every 0.6 meter and the induction of a seismic source to identify stratigraphic layers (as reflectors) and potential faults and other geologic structure (as anomalies). New methods available within the geophysical industry allow the imaging to be focused on the subsurface zone from about 7 to 45 meters below the ground surface providing highly detailed results.

This method will identify the location of geologic anomalies; however, it does not provide specific evidence as to whether the anomalies are fault related. If anomalies are identified in the geophysical data, a subsurface investigation will be required to identify if the anomalies are fault related. The method of subsurface investigation will depend upon physical site constraints as well as site geologic conditions.

A high-resolution shear-wave reflection (HRSWR) technique is commonly applied in areas where deep alluvial sediments or artificial fill materials are present thereby limiting the use of trenching, and/or as a preliminary screening tool to locate anomalies and areas of future subsurface explorations. Shear (S) wave techniques are now being used instead of the more conventional compressional (P) wave technique because S-wave reflection surveys can image shallower structures and have better resolution than P-wave techniques.

Background

Seismic reflection profiling is a standard subsurface mapping technique employed by the oil and gas exploration industry. The use of this reflection technique in non-surface engineering projects has been a relatively recent development, as the formerly high production costs and serious computing requirements were prohibitive. Advances in microelectronics have led to engineering seismographs and personal computer-based processing that now permit the cost-effective use of reflection seismic methods in a wide variety of applications (Steeples and Miller[5]).

Details of the general seismic reflection technique can be found in many comprehensive texts Geldert et al.[6]; therefore, only a brief synopsis of the technique is described here. The seismic reflection method involves projecting a wave down from the surface, and then recording the returning wave back at the surface as it reflects off formations at depth. Seismic energy will also be reflected, refracted, and diffracted at boundaries in the subsurface. The main design consideration for a successful seismic reflection survey is the ability to separate the reflected energy from other arrivals in processing.

The seismic reflection technique can be divided into two categories based on the type of source used. Compressional (P) waves propagate through the earth as a change in pressure and are the same as the sound waves that are heard. Particle motion for P-waves is parallel with the direction of propagation of the wave. Shear (S) waves propagate through the earth by shearing adjacent particles. Particle motion in S-waves is perpendicular to the direction of wave propagation.

The S-wave technique is valuable for two main reasons. First, for a given frequency, shear waves will have approximately one-half to one-eighth the wavelength of the corresponding P-waves. This is due to the fact that S-waves travel at about one-half and as little as one-eighth the velocity of P-waves in the unsaturated and saturated zones, respectively. Although S-waves do not propagate as far through the earth as P-waves, when offsets are short (such as in environmental or engineering applications), shear waves will provide approximately twice the resolution and can image structures at shallower depths. Secondly, S-waves cannot propagate through liquids or gases, as these forms of matter have no shear strength. Thus, S-waves are much more sensitive to fracturing than P-waves, making them the most useful tool for finding and delineating fractures. The frequency content of seismic reflection data is function of both the energy source and the earth through which the energy travels. Vibratory sources have control of the frequency input to the ground, unlike impulsive sources such as a hammer or explosive.

A proprietary electromechanical microvibrator (microvib) has been used as the shear wave source. The unit is compact and light enough for two persons to move, while still emitting a strong enough signal to project S-waves out to the farthest geophones. A photograph of the microvib is presented as Figure 8.

Data is recorded using a proprietary land streamer (also seen in Figure 8) which has 96 shear wave geophones mounted at approximately 0.6-meter intervals on a nylon mesh belt. The geophones are coupled to the ground by steel plates mounted below the geophone on the top and bottom of the belt. The land streamer can be used on asphalt or concrete surfaces and is typically towed by a vehicle or pulled by a winch. The land streamer is typically moved forward a station in conjunction with the source, thereby eliminating the need to hot-glue geophones to the surface, lay out and connect about 192 geophones in advance of data acquisition, and continually roll geophones and cable from the beginning to end of the line, thus reducing the amount of time required to perform the survey.

Figure 8. Electromechanical Vibrator (Microvib) and Landstreamer

Data Acquisition and Processing Procedures

At the start of data acquisition, the 96-geophone land streamer is laid out at the beginning of the line and the source is positioned a half station in from the first receiver station. The microvibrator is connected to the seismograph via a trigger cable. When the operator pushes the trigger button in the recording truck, a signal is sent to the vibrator to start the sweep sequence, and the seismograph began recording. Data is transmitted from the seismograph to a computer where seismic acquisition software is used to correlate data, display data, print selected records, and write data to 4 mm data tape. The processing flow for the data is based on a standard common mid point (CMP) reflection processing sequence with modifications for specific conditions at the survey site.

Interpretation of Geophysical Survey Results

An example of the processed seismic section without and with interpretation is presented as Figures 9 and 10, respectively. These figures represent the shear wave reflection data in a trace amplitude format. This format displays the relative signal strength as energy is reflected from various subsurface features using either a color or gray-scale display. The seismic section included herein is displayed using a gray-scale color bar with the white and black representing the highest amplitude negative and positive polarity reflections, respectively. The figures are presented with time in seconds on the vertical axis and station number on the horizontal axis with each station increment equaling a distance of approximately 0.6 meter.

The data quality on the seismic line is excellent with many reflections visible between about 50 and 300 milliseconds. The area containing as much as 9 meters of artificial fill is evident between Stations 10 and 235, as shown in Figure 10. Potential faulting is most easily observed by looking at disruptions in a high amplitude continuous reflector at about 180 ms. The known main trace of the fault in this area is evident at station 235 along with numerous ancillary faults extending from the main trace towards the surface in a flower structure. This faulting extends from about station 160 to 305. Two other structures possibly indicative of minor faults or some other structural feature are evident near Stations 82 and 115 as shown in Figure 10. A subsequent intrusive investigation (i.e., drilling) would be conducted to confirmation the source of these anomalous features.

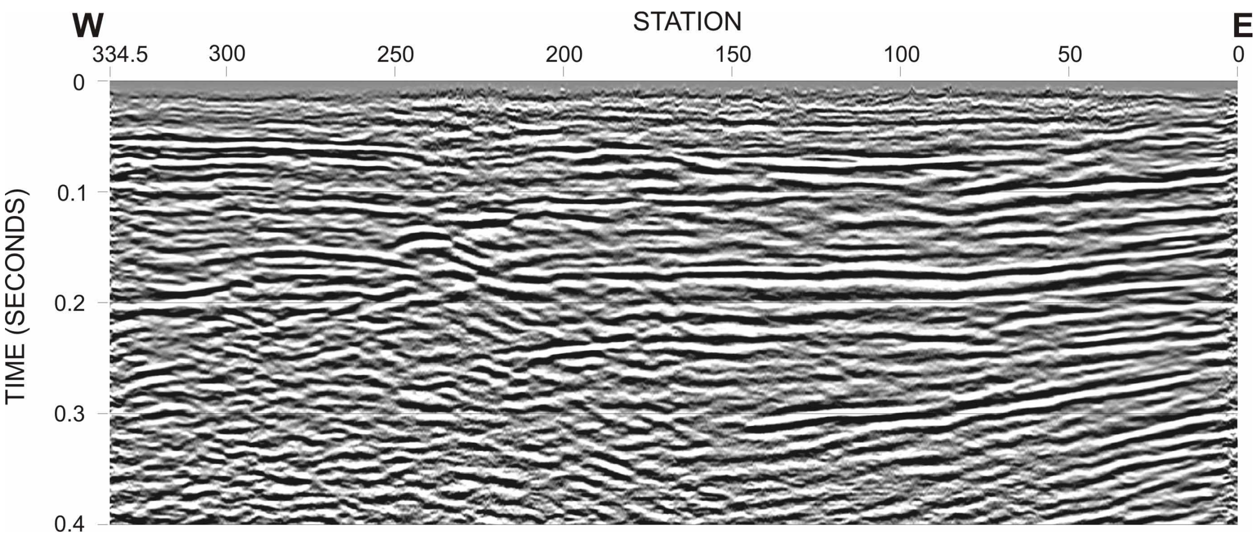

Figure 9. Seismic Profile (Before Interpretation)

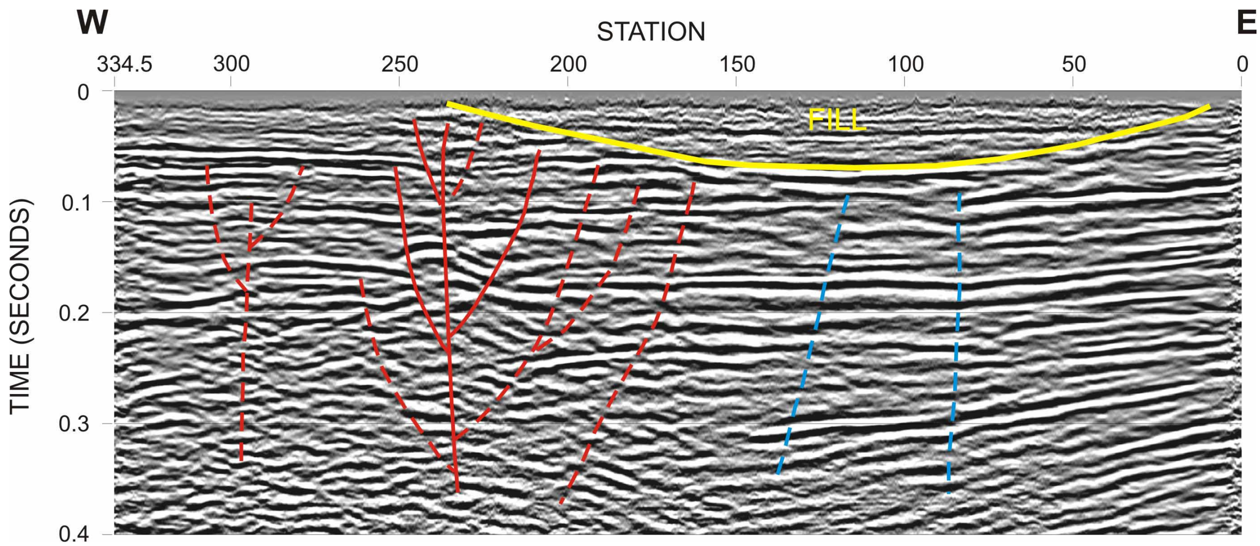

Figure 10. Seismic Profile (After Interpretation)

LARGE-DIAMETER BORINGS

A fourth method of investigating the presence or absence of faults in the shallow subsurface soils is by the use of large-diameter borings. Similar to the continuous-core method, the large-diameter (usually 0.6 meters) borings are drilled along a closely spaced transect using a truck-mounted drilling equipment. This method allows for geologist to directly observe the subsurface geologic conditions by performing a downhole inspection. Boring depths are dependant upon the drilling equipment; however, are typically shallower than 25 meters.

This method is commonly also used in conjunction with any of the previously described methods. The purpose of bucket auger borings is to evaluate the nature of discontinuities inferred from the continuous-core borings, CPTs, or geophysical surveys. If these discontinuous features were determined to be fault related, the faults would be exposed in the boring and a direct measurement of the orientation and what depth these features extend into the section can be observed. This is the only method in which the faults can actually be directly observed (other than trenching), versus being interpreted or inferred. Another advantage of using the large-diameter borings is that it can be used in conjunction with a geotechnical engineering investigation and undisturbed samples can be obtained during the drilling process, thus saving the project additional field investigation costs.

ADVANTAGES OF THE METHODS DESCRIBED

All of the methods described have been proven to be quite successful in dense urban environments. In areas where the depositional environment does not allow for the more conventional trenching, either because of the extensive depth of Holocene deposits (beyond conventional excavation depths) or the physical properties of the sediments is not conducive to open trench excavations, these alternative methods can be utilized. Otherwise, deep and expensive shored trenches would be needed. In addition, these methods allow the investigations to extend beyond the property boundaries (which may be a requirement of the local governing agencies).

The use of continuous-core borings and large-diameter borings allows the geologist to visually observe the effected materials to depths beyond conventional excavation depths. The use of high-resolution geophysical surveys can provide highly detailed imaging of the subsurface and identify the locations of anomalies indicative of faulting, thus reducing the amount of invasive subsurface explorations, or reducing the number of CPTs.

CPTs can provide detailed stratigraphic correlation in shallow subsurface materials across a site. CPTs can be used either a primary screening tool to identify anomalies at a site or as a secondary investigative tool to further identify anomalies in the subsurface.

DISADVANTAGES OF THE METHODS DESCRIBED

The methods described have been proven to be successful at determining the presence or absence of faulting on complex urban environments, whether the complexity is due to physical constraints such as existing buildings, property boundaries and infrastructure, or due to extensive thickness of Holocene deposits. Unlike trench excavations, however, these methods do not always provide an absolute determination of the presence of faulting, primarily because there is not a continuous direct observation of the alluvial deposits. Each of these methods requires extensive interpretation by qualified geologist working in the field as well as in the office. These methods are costly and generally consume greater amounts of time than an investigation by open trench excavation.

The continuous core method requires interpretation of the core material after the field investigation as well as interpretation between borings.

The use of cone penetration testing is also highly dependant upon qualified geologists to perform the interpretation; it does not allow for visual observation of the subsurface materials and requires some type of subsurface explorations to correlate and confirm the results of the CPT data. CPT data is difficult to use in certain areas where the geologic depositional environment resulted in discontinuous layers of sediments. Utilizing CPT data in fault investigations is most successful when used in low energy depositional environments, such as flood plains, or fluvial environments where overbank sediments are deposited over long lateral distances, or in marine environments where rates of sedimentation are more constant and sediment layers extend over large lateral distances. Conversely, it is difficult to correlate sediments between CPTs in an active or recently active stream channel environment, at the mouth or source area of an alluvial fan, or in other areas where the sediments were deposited in an area of high-energy deposition.

Although the geophysical survey can provide detailed imaging of the subsurface conditions, it is primary used as a preliminary screening tool and additional subsurface explorations are also required to correlate the results and to determine the cause of any anomalies observed in the geophysical profile.

The main disadvantages to the use of large-diameter borings would be the possible presence of loose or gravelly sands that present a potential caving hazard and threaten the safety of personnel entering the borings. Additionally, this method cannot be used in areas of shallow ground water. Although large-diameter borings allow for direct observation by the geologist, it requires large amounts of time in the field, as well as requires interpretation of the geologic conditions between the boring locations.

CONCLUSIONS

It is often necessary to use a combination of several methods when performing fault rupture hazard investigations in urban environments where it may not be feasible to use direct observation in trenches. As described above, the methods of field investigation will vary depending on the physical and geologic constraints of the project site. Additionally, the benefit to the project and cost considerations must be taken into account when developing a scope of investigation. In the case of cone penetration tests (CPTs), like the geophysical survey methods, they can be used as a primary screening that can detect anomalies within the subsurface. However, the CPTs can also be used as a investigative tool to further investigating anomalies identified in the subsurface by geophysical survey methods. The anomalies must be further investigated to evaluate if the cause of the anomalies if due to faulting, dispositional environment, or another type of phenomena. By performing an initial screening, the amount of subsurface explorations can be reduced to only the areas bounding the anomalies. This subsequent investigation would likely consist of continuous-core borings and/or large-diameter bucket-auger borings. However, the subsequent investigation could also consist of CPTs with strategically placed continuous-core borings to verify stratigraphic interpretations and correlations of sediments between CPTs. The use of CPTs as a primary screening or secondary investigative methods would depend on key factors such as the depositional environment of sediments in the area being evaluated, the anticipated recovery of the soils in a boring, cost, and time considerations. In any case, the subsequent investigation must also be utilized to correlate and confirm the results of the preliminary data, evaluate for the presence of pedogenic soil horizons and relative age control, and to evaluate for the presence of detrital charcoal for radiocarbon age dating.

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