Evaluation of liquefaction potential at Chapar-Abad Dam, Iran

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ABSTRACT
One of the most common causes of failure in dam site during earthquakes is the development of liquefaction phenomena in saturated and cohesionless deposits. The potential of liquefaction of Chapar-Abad Dam site is evaluated regarding site geology, seismicity, and geotechnical variables including the SPT results of the alluvial deposits. Recently modified relationships of some correction factors such as stress reduction factor (r_d), earthquake magnitude scaling (MSF), overburden correction factor (K_σ), cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) are used. It is concluded that with regards to soil size particle distribution curves, soil type, site seismicity, the calculated variables, and the derived factor of safety, the site susceptible to high potential of liquefaction.

RÉSUMÉ
L'une des principales causes de l'échec en barrage au cours de tremblements de terre est le développement de la liquéfaction phénomènes saturés et cohesionless dépôts. Le potentiel de liquéfaction de Chapar-Abad barrage est évaluée en ce qui concerne la géologie du site, sismicité, géotechniques et variables, y compris les tubes et tuyaux sans soudure résultats des dépôts alluviaux. Récemment modifié les relations de certains facteurs de correction tels que le stress facteur de réduction (e), tremblement de terre de magnitude échelle (MSF), de surcharger facteur de), le stress rapport cyclique (RSE) et la résistance rapportσcorrection (K cyclique (CRR) sont utilisés. Il est conclu que, au regard de la taille des particules du sol courbes de distribution, le type de sol, site sismicité, le calcul des variables et des dérivés facteur de sécurité, le site sensibles à fort potentiel de liquéfaction.

1 INTRODUCTION

The term liquefaction is used to describe a variety of phenomena that causes soil deformations resulting from monotonic, transient, or repeated disturbance of saturated and cohesionless soils under undrained conditions (Kramer, 1996). Significant efforts have been made to assess liquefaction of soils during earthquake in the recent years. Soils that are susceptible to liquefaction are deposited in a narrow range of sedimentary environments in which consist of uniform grain size distributions. According to Papathanassiou et al (2005), alluvial deposits could be considered as liquefiable when their liquid limit (LL) and plastic index (PI) are in the range of 24% and 3%, respectively. Singh et al (2005), noted that the saturation of alluvial deposits has a great effect on triggering liquefaction at a number of earth dams during Bhuj Earthquake in India. According to Xenaki and Athanasopoulos (2008) the liquefaction resistance of gravely material is strongly affected by its relative density and when the relative density is over 55% the material shows stable condition under the effect of common earthquake events.

The occurrence of liquefaction in soils is often evaluated using the simplified procedure originally proposed by Seed and Idriss (1971) based on the Standard Penetration Test (SPT). The current paper aims at presenting the liquefaction potential assessment of Chapar-Abad Dam on the basis of local geology, seismotectonics and geotechnical variances.

The dam is an inhomogeneous earth-fill type with height and crest length of 44.5 and 427 meters, respectively, and a reservoir capacity of about 127 million cubic meters. It is located about 75 kilometres Southeast of Uromieh City, in West-Azerbaijan Province (see Figure 1). The dam foundation rests on over 60 meters of alluvial deposits in which overburden bedrock layers of carbonate units. The abutments consist of carbonate and schistose layers of Precambrian age.

2 GEOLOGICAL SETTING

The area contains three types of lithology belonging to Pre-Cambrian, Palaeozoic and Quaternary deposits The Pre-Cambrian rock covers almost 50% of the land surface and it comprises three types of lithology which are categorized as highly metamorphic rocks predominantly amphibolites, genies and marble, a mixture of slightly metamorphic rocks (phyllite and schist) and alkaline volcanic rocks, and finally a sequence of highly fractured limestone and shale. The later is known as Baroot Formation and makes up the basement and the abutment of the dam site. The Palaeozoic rocks have limited appearance and are composed of sandstone (Laloon Formation) and a series of limestone; dolomite and shale (Mila Formation) which belong to early and late Cambrian respectively. The other outcrop is Ruteh Formation with its predominant lithology which is thick to medium bedded limestone. Most of the Palaeozoic rocks form the base of the reservoir. They are very small and scattered outcrop of Mesozoic and Cenozoic rocks in the area. Quaternary deposits also cover large portion of the area and are recognized as old alluvium and terrace deposits, younger alluvium deposits, accumulation of debris deposits at the footage of the slopes, and recent alluvial deposits along the flowing streams and rivers. The geological setting of the site is shown on Figure 2.

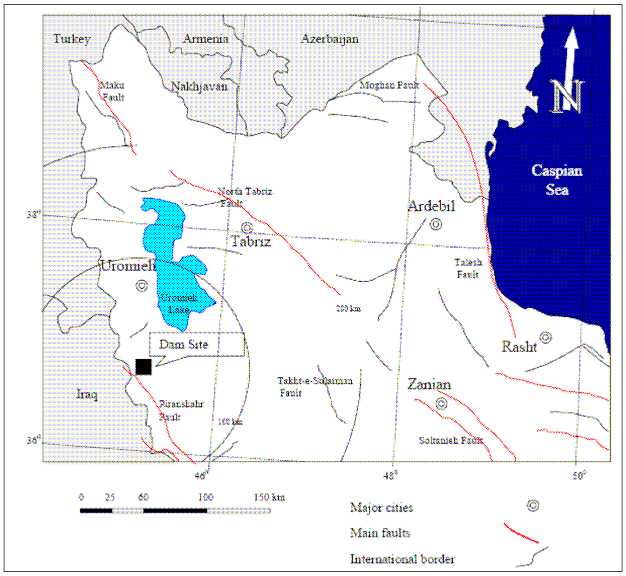


Figure 1, Geographical location of Chapar-abad dam and distribution of major faults in the area.

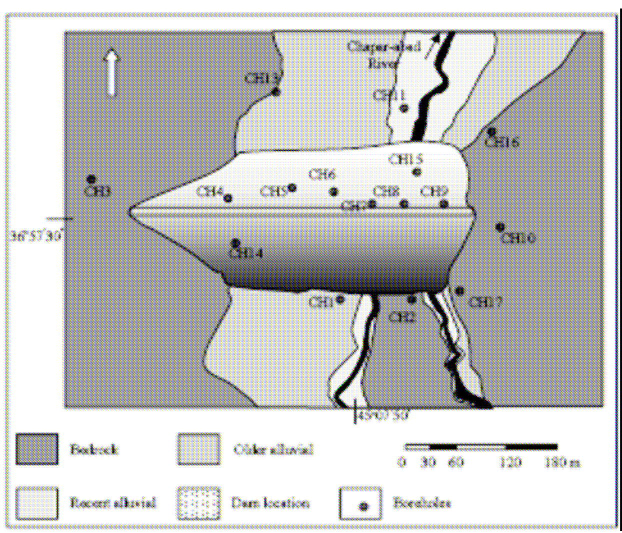


Figure 2, Geological setting of Chapar-Abad Dam and location of bore-holes

The dam site was selected on an unsymmetrical and relatively wide river valley in which the slope of the right abutment is greater than the left abutment. The alluvial deposits at the dam foundation exceed the height of the dam and they generally consist of wide range of granular soils including sand, silt and gravels.

3 SUBSURFACE GEOLOGY

In order to evaluate the engineering geological properties of the alluvial deposits, a number of boreholes were drilled at the dam site (see Figure 2). Total length of 493 m of drillings was carried out in alluvial deposits. Standard penetration tests (SPT) in each borehole were taken at an interval of 1.5 m and in-situ permeability tests were also conducted along the boreholes. Collections of undisturbed/disturbed samples for laboratory testing were also taken. The analysis of the borehole data shows that the strata in general comprises clayey silt soils to sandy silt, sand and gravels. According to the Unified classification method, the alluvial deposits were classified as CL, SM, SC, GC, GM, and GW. The soils on the left bank were of much finer grains, on the other hand, the coarser grain soils were more concentrated on the right bank and transition zones were also observed between the main named soil deposits. The details of soil deposit distribution along the dam axis are shown on Figure 3 and the soil size distribution curves are presented on Figure 4. The results of direct shear box tests showed that the friction angles of the coarse grain soils are in the range of 30 to 35 degrees.

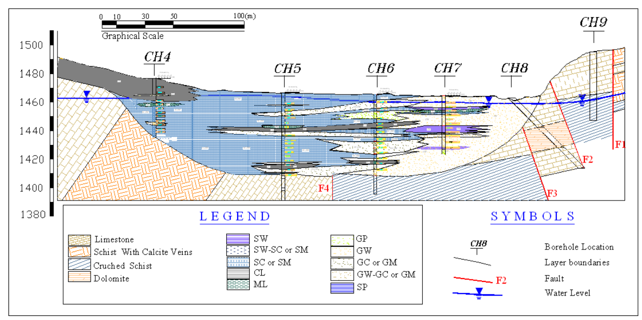


Figure 3, Details of soil type and their distribution along the dam axis.

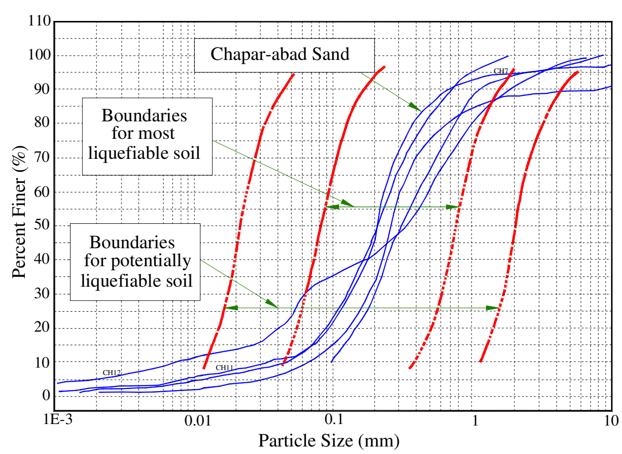


Figure 4, Ranges of grain size distribution at Chapar-abad dam foundation with respect to Tsuchida's liquefaction susceptibility chart.

Field permeability test results indicate various values of permeability, from 10^{-2} (cm/s) for the right bank, and 10^{-7} (cm/s) for the left bank. But in general the average values of permeability for alluvial deposits were in the range of 10^{-3} to 10^{-5} cm/s. Figure 5, illustrates the permeability variations along the dam axis.

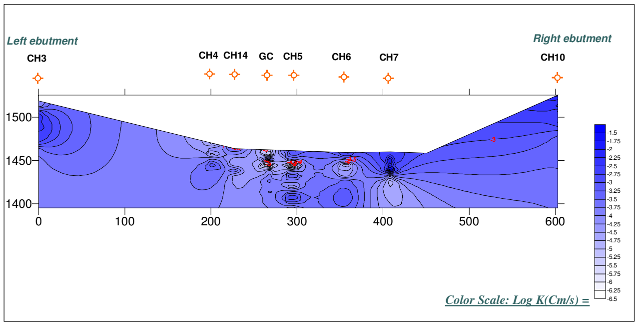


Figure 5, Permeability cross section along Chapar-Abad Dam axis.

4 SEISMICITY

Iran lies in a wide boundary that separates the Arabia and Eurasia plates. Earthquakes in Iran and neighbouring regions are closely connected to their position within the geologically active Alpine-Himalayan belt (Jackson et al. 1995). Chapar-Abad Dam is located in a highly seismic zone within the Azerbaijan Provinces. This zone often feels deep-seated earthquakes and the focal depth are in the range of 30-100 km (Engdahl et al. 2006). There are numerous faults in the region and hence are extremely vulnerable to seismic activities. Seismic effects of the region vary within the dam site depending on the geological, geomorphological and geotechnical conditions.

Location of major faults within the dam site is presented on Figure 1. Two major faults have direct effect on the dam site seismicity in which includes Piranshahr fault and Tabriz fault. The studies showed that Piranshahr fault has the ability of producing an earthquake of 7.5 magnitudes and generation a maximum acceleration of 0.44g (West Azerbaijan Water Authority, 2002). Tabriz fault is an active fault with a reoccurrence time interval of 250 years; the average displacement is about 2 meters for each event (Masson et al. 2006). Since the fault did not generate large earthquake during the last two centuries, therefore, a new large earthquake may occur on Tabriz fault during this century. Although the fault is located about 150 kilometres NE to the dam site, but it can produce a maximum acceleration of 0.28g at the dam site location (West Azerbaijan Water Authority, 2002).

5 LIQUEFACTION ASSESSMENT

Number of case histories of liquefaction induced ground deformation and their effects on constructed facilities were considered by many researchers. For example: Dharmaraju et al. (2007) studied the potential of liquefaction of Chandigarh City, India, with respect to different peak ground motion parameters. Zhang et al. (2004) estimated lateral displacements associated with liquefaction using SPT and CPT tests results. Dynamic properties and liquefaction potential of soils in response to earthquake event were considered by Sitharam et al. (2004). Laue and Buchheister (2005) established the liquefaction susceptibility of soils in accordance with load path, load direction and loading velocity. Xenaki and Athanasopoulos (2003) studied the effect of fines content on the liquefaction potential of mixture of fine soils.

The simplified procedure based on SPT as proposed by Seed and Idriss (1971) in which was adopted by Youd et al. (2001), has become a standard practice worldwide. The same procedure has been used for assessment of liquefaction potential in the present study.

Volume change behaviour in soils during liquefaction is related to the variation of pore pressures development. This behaviour is primarily depended on particle shape, size, and gradation. The bounds on size criteria are broad and range from non plastic silts to gravel, however most liquefaction is observed in clean sands. Well-graded soils are generally less susceptible to liquefaction than poorly graded soils. According to (Kramer, 1996), most liquefaction failures in the field have involved uniformly graded soils. The first step to evaluate the potential of liquefaction could be the identification of soil size particles. The soil particle distribution of Chapar-Abad Dam site and restriction of liquefaction susceptibility based on Tsuchida (1971) are presented on Figure 4. It can be noted that the soil particles at Chapar-Abad Dam is located between the boundaries of most liquefiable soil.

Liquefaction potential of an area is usually evaluated by two seismic parameters expressed as;

- Cyclic Stress Ratio (CSR) in which indicates the seismic influences on soil deposit,
- Cyclic Resistance Ratio (CRR) in which represent the soil capacity to resist liquefaction.

5.1 Cyclic Stress Ratio (CSR)

The value of CSR can be calculated by the use of equation [1] in which was introduced by Seed and Idriss (1971).

$$CSR = (\tau_{av} / \sigma') = 0.65(a_{\max} / g)(\sigma / \sigma')r_d \qquad [1]$$

Where τ_{av} is average shear strength, σ and σ´ are total and effective overburden stress, respectively, a_{max} is peak horizontal acceleration during an earthquake, g is gravitational acceleration, and r_d is stress reduction factor.

For noncritical projects, equation [2] is suggested by Youd et al. (2001) can be used to estimate the average values of r_d with respect to depth. The calculation of values of r_d may also be done by the use of equation [3] which is introduced by Blake and recommended by Youd et al. (2001).

$$r_d = 1.0 - 0.00765z \qquad \text{for } z < 9.2 \text{ m} \qquad [2a]$$
$$r_d = 1.174 - 0.0267z \qquad \text{for } 9.2 < z < 23\text{m} \qquad [2b]$$

$$r_d = \frac{(1.000 - 0.4113z^{0.5} + 0.04052_z + 0.001753z^{1.5})}{(1.000 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.00121z^2)} \qquad [3]$$

where z, is depth beneath the ground surface in meters.

Ranges of stress reduction values r_d with depth are shown on Figure 6, where the average values of r_d for Chapar-Abad Dam estimated from equations [2] and [3] are also plotted and showed as dotted line.

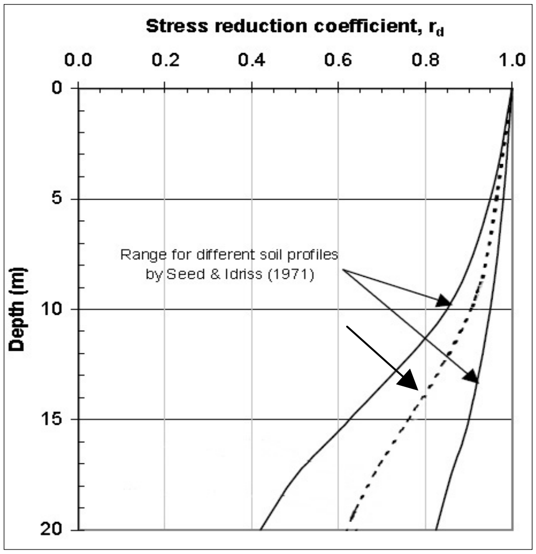


Figure 6, Range of stress reduction coefficient values variation with depth.

5.2 Cyclic Resistance Ratio (CRR)

Evaluation of cyclic resistance ratio (CRR) is usually made according to standard penetration test (SPT) results. Many formulas are developed to estimate the value of CRR regarding the soil size and percentage of fine content. The following equation proposed by Rauch (reported by Youd et al. 2001) is used for clean sand.

where N_{60} is the SPT number for depth of less than 30 meters and $CRR_{7.5}$ is cyclic resistance ratio to estimate the capacity of soil to resist liquefaction during an earthquake of magnitude 7.5. The value of $CRR_{7.5}$ can be adjusted for the magnitude of the earthquake under consideration by the following equation.

$$CRR = CRR_{7.5} * MSF \qquad [5]$$

where MSF is magnitude scaling factor. The values of MSF for Chapar-Abad Dam site is presented on Figure 7.

Since the maximum acceleration of 0.44 g is calculated for an earthquake of 7.5 magnitudes, at Chapar-Abad Dam site, then the value of MSF will be 1.0346.

The value of CRR should also be adjusted regarding the overburden pressure. The adjustment can be made by the use of a correction factor (K_σ) as in the following equation which is suggested by Idriss and Boulanger (2006).

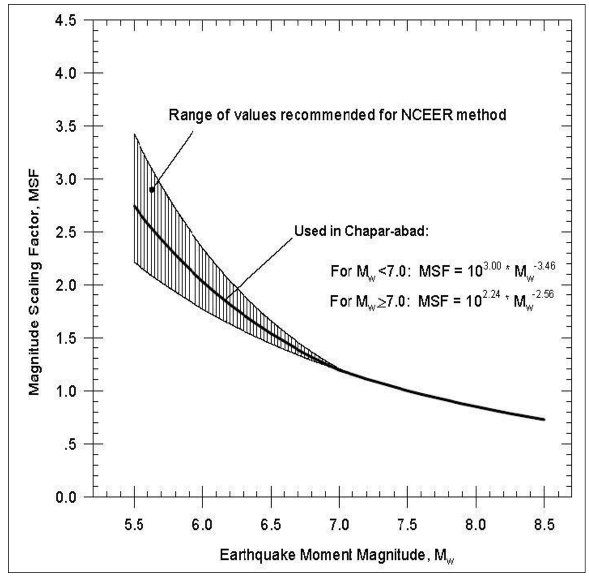
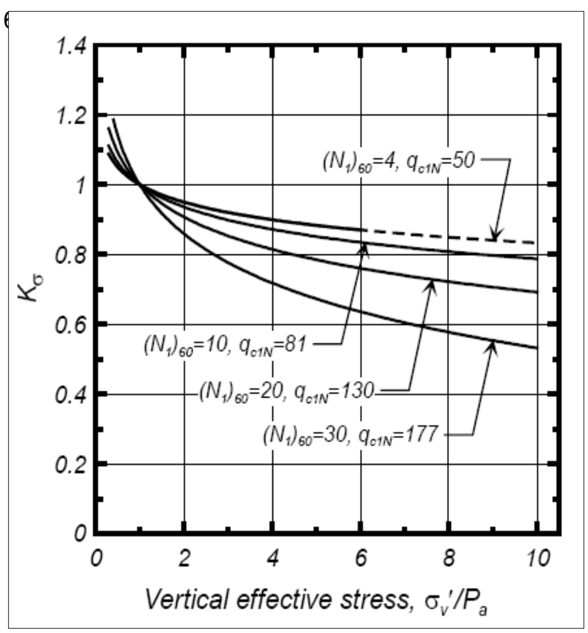


Figure 7, magnitude scaling factors for computing CRR

The value of (K_σ) can be obtained from curves shown on Figure 8 for different N_{60} values and overburden pressures.

$$CRR_{7.5} = \frac{1}{34-(N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{\left[10.(N_1)_{60}+45\right]^2} - \frac{1}{200} \qquad [4]$$

Figure 8, Values of Kσ correction factors (from Idriss and Boulanger, 2004)



$$CRR = CRR_{7.5} * MSF * K_\sigma \qquad [6]$$

LIQUEFACTION POTENTIAL AT DAM SITE

Based on the corrected values of SPT test results, and the calculated values of CRR and CSR, the assessment of liquefaction potential at Chapar-Abad Dam foundation is performed. Figure 9, shows the boundary curves for the factor of safety (FC =15%) and (FC≤5%) derived by Idriss and Boulanger (2006) together with SPT data of Chapar-Abad Dam site. The plots are considered for a case of clean sand, overburden of 1 atmosphere, and an earthquake magnitude of 7.5. It can be noted that most of the boreholes result (SPT data) are situated above the curve line which indicate high potential of liquefaction along the dam foundation.

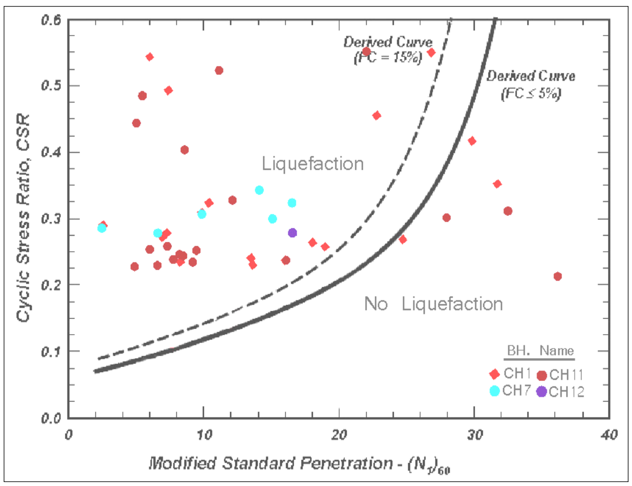


Figure 9, Correlation between CSR and SPT result for the assessment of liquefaction potential at Chapar-Abad Dam.

The factor of safety (FS) of a site to resist liquefaction can be determined from the following equation;

$$FS = CRR / CSR \quad [7]$$

The values of CSR, CRR and FS versus depth for each borehole are plotted on Figure 10. It can be observed that good correlations could be established between these variables and the type of soil within the alluvial deposits along the river bed. It can also be noted that the variations of FS curves are mostly dependent on the variations of CRR curves. Finally the curves can indicate the depth and thickness of layers that are susceptible to liquefaction.

7 CONCLUSIONS

Liquefaction potential at Chapar-Abad Dam is evaluated on bases of geological setting, site seismicity, and geotechnical information including SPT data. The alluvial deposits of the dam site showed high potential of liquefaction regarding the following situations;

- The range of particle size of alluvial deposits lied within the boundaries of most liquefiable soils.
- The area faces earthquakes of magnitudes 7.5, in which the value of MSF is estimated.
- With regards to the percent of fine content most of the (FC%) and the calculated CSR, most of the SPT records are located in the liquefaction zone.
- The plots of FS versus depth can be used to evaluate the variation of liquefaction potential regarding the soil type and layer thickness within the alluvial deposits beneath the dam axis.

It is recommended that the site should strengthen by the use of different means of modifications methods.

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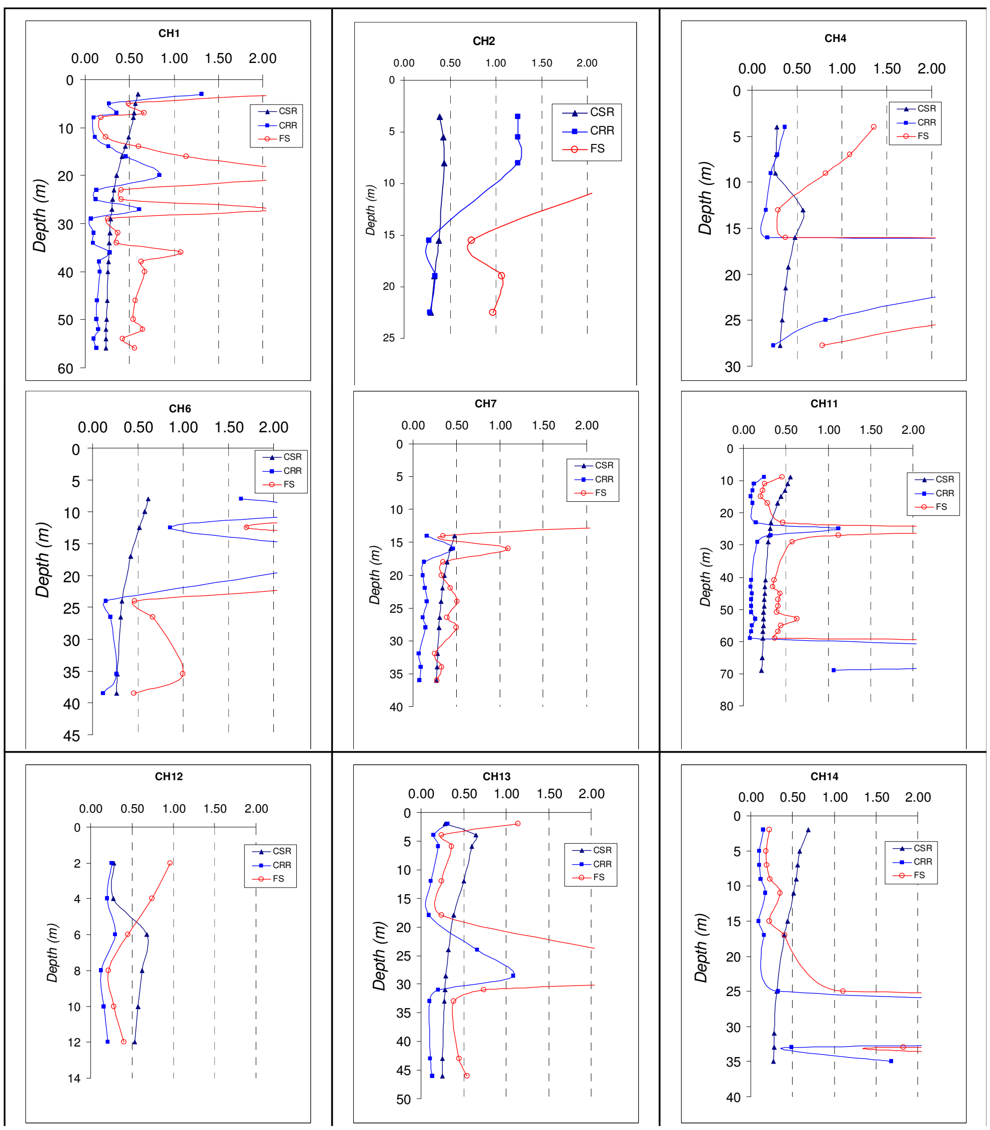

Figure 10, Plots of CSR, CRR, and FS versus depth for different borehole locations