Evaluation of Liquefaction Potential of Sandy Soil from Cyclic Simple Shear Test-A Case Study

Suresh Maurya[1], Uday B. Chakraborty[2] and Honkanadavar N. P[3]

[1]Scientist 'D', CSMRS, Ministry of Jal Shakti, Deptt. of WR, RD & GR, New Delhi -110016
[2]Scientist 'C', CSMRS, Ministry of Jal Shakti, Deptt. of WR, RD & GR, New Delhi -110016
[3]Scientist 'E', CSMRS, Ministry of Jal Shakti, Deptt. of WR, RD & GR, New Delhi -110016

Abstract. The most common cause of ground failure during earthquake is the liquefaction phenomenon. This paper deals with estimating the liquefaction potential of soils obtained from difficult terrain condition with high degree of soil heterogeneity. Case study of Shahpurkandi Dam, Punjab have been considered, studied and presented. Samples of sandy soil collected from foundation with depth ranging from 8.5 to 20.0 m were studied for grain size analysis, relative density, liquid limit, plastic limit and plasticity index and discussed in this paper. Undrained cyclic simple shear tests were examined on saturated specimens with confining pressure ranging from 0.1 to 0.4 MPa for determining cyclic strength to cause liquefaction. Seed's procedure has been used to find out cyclic stresses induced by different earthquake magnitude of 6.0 and 8.0 with their respective peak ground acceleration (PGA) value of 0.17 g and 0.20 g. It is observed that the cyclic strength in all the cases is more than the cyclic stresses induced. Hence the foundation is not susceptible to liquefaction except for depth at 8.50 m for a magnitude 8.0, where sand deposit is found to liquefy. To avoid liquefaction, it was suggested to consolidate the foundation, so as to increase the cyclic strength to nullify the liquefaction. Higher PGA value of 0.24 g was also employed to understand liquefaction potential at various depths. Therefore, cyclic strength of soil should always be more than induced cyclic stress to conclude that the deposit is sufficiently dense and not susceptible to liquefaction.

Keywords: Liquefaction, Sand, Cyclic Strength, Cyclic Stress, Earthquake

1. Introduction

Liquefaction phenomenon on the deposit of sand was first explained by Casagrande in 1936 with the help of critical void ratio. He explained that when deposits of sand having void ratio larger than critical void ratio, it tends to decrease in volume when subjected to shear. Dense sand having void ratio less than critical void ratio, under similar condition tends to dilate. The void ratio at which no change in volume occur when subjected to shear is called critical void ratio. If the stress remains constant and drainage is prevented, the pore water pressure increase and effective stress decreases. This will reduce the shear strength of soil. When the shear strength is reduced to a value less than applied shear stress, the soil may fail in liquefaction. Liquefaction can lead to many types of failures, such as loss of bearing capacity in foundation soil, floating of buried structures, spreading of soil in lateral direction, dislocation of retaining structures, sinking or tilting of structure, landslides etc.

Critical void ratio may not be sufficient to justify liquefaction potential of sand layer. There are many other factor responsible like confining pressure acting on sand layer, intensity and duration of ground shaking etc. Critical void ratio is a variable value and changes with change in confining pressure. Effect of volume change in dynamic condition is much different than static load condition simulated in direct shear or triaxial shear test [1]. Loading in dynamic condition can be best realized in laboratory test like cyclic simple shear test having smooth rotation of principal stress direction.

India has a huge hydro-power potential and major portion of which is still unexploited. There have been tremendous efforts for water resources development projects for harnessing hydro-power. Most of the sites are situated in the Himalayas, the majority of which lies in the zone IV & V of the seismic zonation map of the country [2]. Over 59 % of India's land area is under threat of moderate to severe seismic hazards [3]. Therefore liquefaction potential and dynamic soil properties are needed for the design of a large number of civil engineering structures situated in seismically active areas which are subjected to dynamic loads One such case study of Shahpurkandi Dam, Punjab has been presented in section 7 where inference of laboratory test to cyclic stress induced due to the earthquake has been compared to bring out the susceptibility of soil to liquefaction.

There are many variations of dynamic tests to evaluate liquefaction testing and dynamic properties and the user should select the one that is most accurately simulating the conditions in the field. One of the methods describe in this paper is the cyclic simple shear test. This test has advantage over other test in terms of inducing cyclic shear stresses that reverse direction many times during the earthquake. Also it simulates the smooth and continuous rotation of normal stress during shear.

2. General Concept of Ground Shaking

Consider stresses acting on soil element without ground shaking as shown in Figure 1(a) and with ground shaking as shown in Figure 1(b).

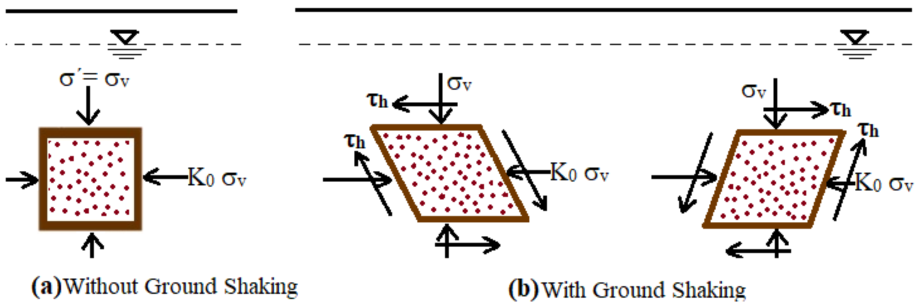


Fig. 1. Representation of stresses on a soil element at rest and during ground shaking

When the ground shaking effect is not present, the initial effective stress on the soil is equal to σ' which in term of vertical effective stress is equal to σ_v and horizontal effective stress equal to σ_h=K_0 σ_v, where K_0 is the earth pressure coefficient at rest. When the ground shaking is due to earthquake, a cyclic shear stress τ_h will be developed on the soil element. Ground shaking reverses its direction many times during the earthquake, making it a significant factor in determining liquefaction potential.

Hence, to understand liquefaction problem in the laboratory, it must simulate the combination of constant normal stress and cyclic stress on the plane of the soil element. The onset of liquefaction depends on the application of a requisite number of stress or strain cycles to which a soil is subjected.

3. Cyclic Simple Shear Device

3.1. Importance of Cyclic Simple Shear Device

The cyclic simple shear device is the most desirable machine for reproducing the effects of an earthquake on soil samples. It provides a reasonable close simulation of the stress induced on a soil element by one component of earthquake motion in the field i.e., horizontal acceleration (which is 0.5 to 0.67 times higher than vertical acceleration). It is capable of reproducing stresses induced by earthquakes much more accurately than the cyclic triaxial test. With simple shear device the principal stress directions on the sample experience a smooth and continuous rotation during shear as it occurs in the field. Expressing the data in terms of the cyclic shear stress and normal effective stress on the horizontal plane is very much useful for engineering purposes.

3.2. Test Operation

Cyclic simple shear test is the most reliable method for measuring cyclic shear strength of undisturbed or compacted soil samples. It determines the number of cycles to liquefaction and dynamics properties. Test condition defines the normal and shear stress acting on the top face of a specimen. Normal and shear load is measured with the help of vertical and horizontal load transducer. Bottom face of the specimen is fixed and the radial strain on specimen is zero. Saturated sample is consolidated under a normal constant load.

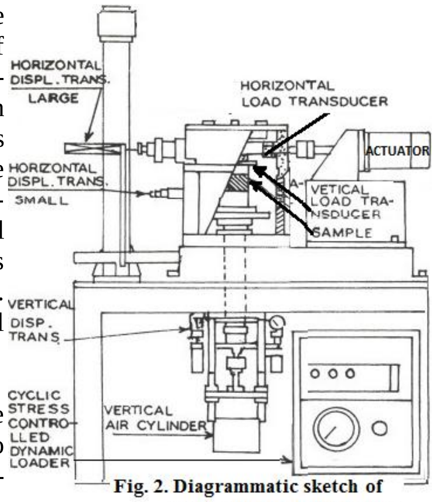


Fig. 2. Diagrammatic sketch of cyclic simple shear device

Schematic sketch of cyclic simple shear device is shown in Figure 2. Vertical actuator helps to keep the constant normal load during consolidation phase of test and also permits application of force for consolidation increment. Once consolidation is complete, a horizontal shear stress (cyclic shearing) is applied to one end of the sample through the pheumatic actuator. The test procedure is based on the constant volume testing of soils. The sample height is continuously maintained during shear to ensure constant volume. The cyclic strength of a soil is determined based on the number of cycles to reach liquefaction or double amplitude exceeds 10 % strain. Liquefaction results are 100 % change in excess pore water pressure ratio under constant volume (i.e., excess pore water pressure divided by effective vertical stress). Standard test method (equipment, specification and testing procedure) for cyclic direct simple shear test is available in the ASTM code published in 2019 [4].

3.3. Limitation of Cyclic Simple Shear Device

Cyclic simple shear condition provides a better evaluation of the liquefaction testing. The only shortcoming is that the test cannot be made to impose uniform pure stresses because only the top and bottom planes are subjected to a shear stress but the required shearing stresses in the field happen on both lateral as well as vertical plane in a complex manner as shown in Fig 3. To reduce effect of non-uniform stress, size of the specimen is prepared in a controlled height with diameter to height ratio of at least 4 to 1.

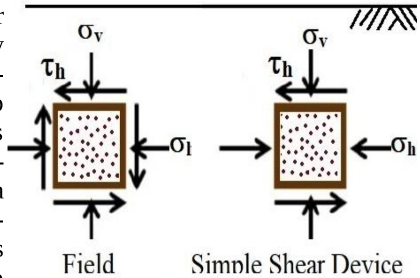


Fig. 3. Expression of stresses in field and in cyclic simple shear device

4. Factors Affecting Liquefaction

There are number of factors affecting liquefaction occurrence, but the most important factor which affect in the field are listed here.

1. **Type of soil:** Saturated fine sands are more prone to liquefaction than coarse sand, gravel, silts or clays. Uniformly graded sand is more vulnerable than well graded sand. Liquefaction may not occur when there is a substantial amount of silt in sand. But medium to fine sand is more susceptible to liquefaction; especially in the upper deposit of 5 m.

2. **Relative Density**: Soil in a denser condition may not liquefy, but same material in loose condition may liquefy. In dense sands, both pore water pressure and settlement are considerably less than those in loose sands. Chances of liquefaction are extensive when RD is less or about 50%. But when RD is > 70 %, number of cycles to cause liquefaction or 10% double amplitude, strain increases significantly.

3. **Confining pressure.** Presence of confining pressure increases the shear stress required to initiate liquefaction under cyclic load. The transfer of stress from soil particles to the pore water is delayed. Thus sand deposit would require higher intensity vibration for greater duration. In Niggata (Japan) earthquake, at various locations, soil remains stable under deposited fill, but similar surrounding soil without fill liquefied largely.

4. **Intensity (magnitude of stress or strain) induced due to ground shaking:** Ground shaking intensity depends upon earthquake magnitude, distance from energy source and max. ground acceleration. Therefore its assessment must be considered an important factor in determining the occurrence of liquefaction. Past earthquake in Japan has shown that liquefaction occurred whenever ground acceleration is in excess of 0.13 g [5].

5. **Requisite number of Stress or strain cycle induced due to ground shaking:** Characteristics of ground shaking like vibration velocity, acceleration, amplitude and frequency are important. Liquefaction usually occurs only after a certain number of vibration cycles are repeated which depends upon the duration of ground shaking.

The occurrence of liquefaction is also affected by many other factors such as soil properties, grain characteristics, age of soil deposit, local geology etc. The likelihood of the ground to liquefaction increases if the ground is a loose sandy deposit, the ground water table is shallow, the ground is saturated and the earthquake intensity is high and for a longer duration.

5. Various Methods to Assess Liquefaction Potential

Various methods to assess liquefaction potential are presented in Table 1.

Table 1. Various methods to assess liquefaction potential

Sr no	Methods to predict liquefaction	Procedure
1	Simplified procedure developed by Seed and Idriss,1982 [6]	A comparison of the cyclic shear stresses induced by the earthquake with those required to cause liquefaction in the same number of stress cycle obtained in laboratory test. This determines whether any zone exists within the deposit where liquefaction can be expected to occur as shown in Figure 4. When the induced stresses exceed those required to cause in the laboratory is the indication of liquefaction.
2	Grain size characterisation	The grain size curve of the soil at the site can be incorporated in the standard gradation curves for liquefiable and non-liquefiable soils to find out whether a particular type of soil falls between the boundaries for most or potentially liquefiable soils.
3	One dimensional wave propagation theory	Ground response analysis is used to obtain the induced dynamic shear stresses. The liquefaction can be estimated by comparing the equivalent uniform cyclic shear stress obtained from the ground response analysis to the laboratory cyclic shear strength of the soil.
4	Empirical methods	Empirical methods involve estimation of liquefaction potential based on histories of sites where liquefaction did or didn't occur during previous earthquakes. The SPT value or cone penetration resistance is used to differentiate between liquefiable or non-liquefiable soils.

6. Methodology Adopted to Evaluate Liquefaction Potential

Simplified procedure by Seed & Idriss is adopted to investigate liquefaction potential of Shahpurkandi Dam Project, is presented in section 7. Complete evaluation is necessary since soil properties do not change appreciably until liquefaction is eminent. Accordingly Seed and Idriss has developed simplified method for assessing induced stresses (i.e., average cyclic shear stress) due to earthquake motion which is adequately reliable for many practical purposes. Procedure of this method is presented in Table 2.

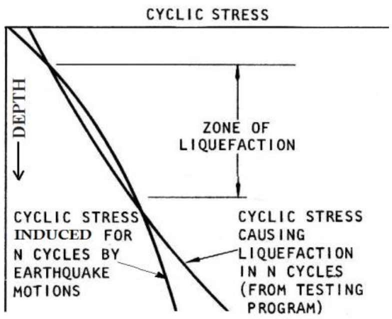
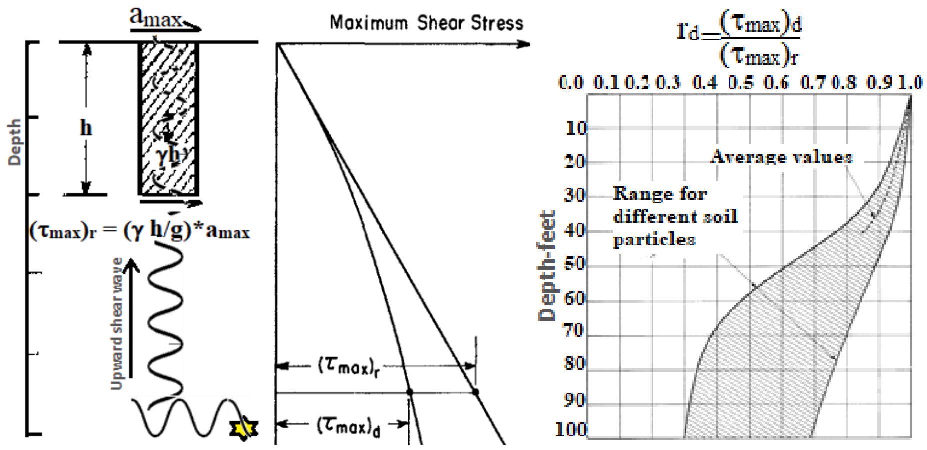


Fig. 4. Comparision of cyclic stress induced vs. Cyclic stress causing liquefaction

Laboratory test are conducted either on the cyclic simple shear device or cyclic triaxial shear device to obtain cyclic resistance ratio (CRR) with respect to number of stress cycles to cause initial liquefaction. The approx. number of significant stress cycle, N corresponds to the earthquake magnitude [5]. CRR with respect to significant number of stress cycle is then employed to find out cyclic strength at various depth of soil deposit. Liquefaction potential is assessed by comparing the average cyclic shear stress induced by earthquake motion with cyclic strength obtained from laboratory test program (See Figure 4). The procedure has limitation that it uses the loading as average equivalent cyclic stresses and the uncertainty of CSR increases with depth dependent stress reduction factor (r_d), when used to simplify calculation.

Table. 2. Assessment of cyclic stress by seed's simplified formula

Steps	Procedure	Maximum cyclic shear stress, τ_{max}
Step 1	Consider the max. ground horizontal acceleration (a_{max}) for soil coulumn at depth h for rigid body (r) as shown in Fig. 5a. *γ = Unit weight of soil, g = Acceleration due to gravity*	$(\tau_{max})_r = (\gamma\ h/g)*a_{max}$
Step 2	Soil column in the field, behaves as deformable body (d). Actual shear stress at a depth h will be less than above equation as shown in Fig. 5b. *r_d= Stress reduction coefficient*. This will decrease from a value of 1 at the surface to much lower value at larger depth as shown in Figure 5c.	$(\tau_{max})_d = r_d\ (\tau_{max})_r$
Step 3	For practical purpose, average equivalent uniform shear stress (induced cyclic stress) is taken as 65 % of the maximum cyclic shear stress. τ_{max} in the irregular stress cyclic is normalised to τ_{avg} as shown in Fig 6.	$\tau_{avg} \approx 0.65(\gamma\ h/g)*a_{max}*r_d$
Step 4	Appropriate number of significant stress cycle, N_c is decided from duration of ground shaking and magnitude of earthquake	
Step 5	Liquefaction potential is assessed by comparing the cyclic shear stress induced by earthquake motion with cyclic strength obtained from laboratory test program	



(a) $\boldsymbol{\tau_{max}}$ of Rigid body **(b)** $\boldsymbol{\tau_{max}}$ of deformable body **(c)** Stress reduction factor

Fig. 5. Determination of maximum cyclic stress ($\boldsymbol{\tau_{max}}$) induced due to the earthquake

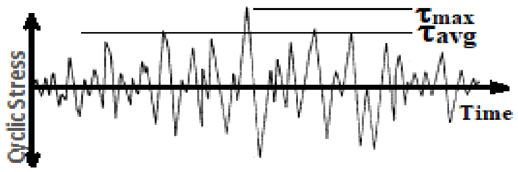


Fig. 6. Average uniform shear stress from time-stress history of earthquake

7. Case Study of Shahpurkandi Dam Project, Punjab

Shahpurkandi Dam, a multipurpose major project [7-8] is being constructed on Ravi River in Pathankot district, Punjab, 11 km downstream from the existing Ranjit Sagar Dam. The project lies in seismic zone IV as per the seismic zoning map of India [2]. It is a 55.5 high concrete Dam with 206 MW power expected capacity and comprising of 7.70 km long hydel channel, 2 nos. head regulators and 2 nos. power houses. It is being constructed to provide uniform release of water to Upper Bari Doab Canal, Kashmir canal and Ravi Canal (J&K). Shahpurkandi Dam project is likely to be completed by 2023. Layout of the project is shown in Figure 7.

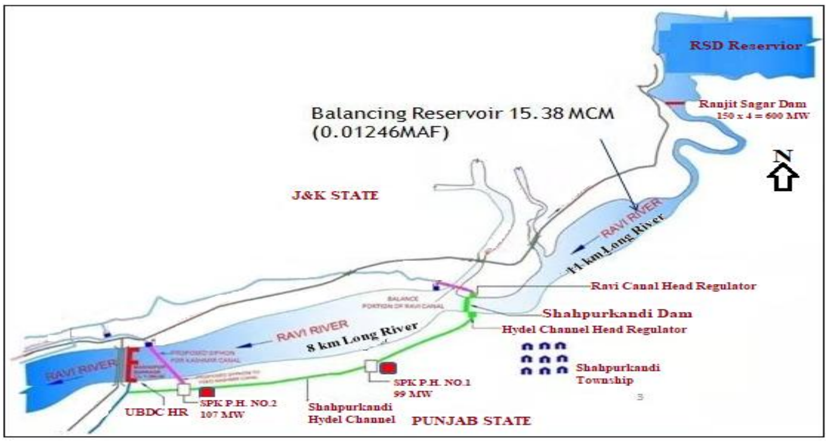


Fig. 7. Layout of Shahpurkandi Dam Project

The completion of Shahpurkandi dam is of utmost importance for optimum utilization of Ravi water for power generation and irrigation. Shahpurkandi Dam will also act as balancing reservoir for working of Ranjit Sagar Power Plant during the peak hours. Reservoir capacity of the project when completed will be 9.47 million cum. Construction work of Dam Project is shown in Figure 8.

Fig. 8. Construction work of dam project

Keeping in view the importance of project, in 2008 Shahpurkandi Dam Project has been declared as 'National Project' by Ministry of Water Resources, Govt. of India with various benefits presented in Table 3.

Table 3. Benefits from the Shahpurkandi Dam Project

Sr.	Benefits from the Shahpurkandi Dam Project
1	Project will create irrigation potential of 5,000 ha. in Punjab State and 32,173 ha. in J&K State
2	Project will deliver electricity and irrigation worth Rs 850 crore annually and to fully utilize the Ravi water as per the Indus Water Treaty
3	Project will enable the U/s Ranjit Sagar Dam project electricity station to act as a peaking station, besides having its own generation capacity of 206 MW.
4	Shall produce 1042MU of electricity annually.J&K will share 20% busbar rate
5	To act as balancing reservoir for optimum utilization of releases from Ranjit Sagar Dam Project. Boost intensive irrigation for 3.48 lakh ha.of UDBC system
6	Shall regulate and ensure uniform supplies to downstream Upper Bari Doab Canal (UBDC), Kashmir Canal and High Level Ravi Canal (J&K)
8	Project will provide silt free water to existing and proposed power houses
9	Development of tourism, recreational facilities and fisheries
10	Overall socio economic development of area

7.1. Laboratory Investigation

Sand layers were encountered at various depths of foundation near the left abutment of the Dam. Project authority felt that this material might liquefy under earthquake motion. To verify the susceptibility of sand deposit to liquefaction, laboratory investigation was conducted on the sand deposit by CSMRS [9-10]. Laboratory investigation consisted of determining index properties of soil and results from cyclic simple shear test. Details of laboratory results collected from CSMRS records are discussed here.

7.1.1. Index Properties of Soil

To identify and characterize the soil, following index properties were determined.

***Grain Size Distribution**:* Grain size analysis was conducted as per IS 2720-Part IV to determine gradation of particle size. The gradation for three tested samples varied in the range from 0.002 mm to 4.75 mm and two tested samples varied from 0.002 to 2.0 mm. Gradation curve of one of the sample is presented in Fig 9.

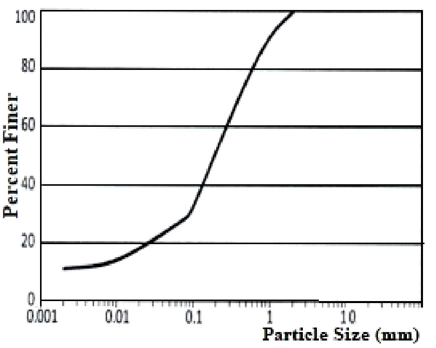


Fig. 9. Grain Size Distribution

Liquid and Plastic Limit: Liquid limit was conducted on Casagrande's device varied from 26.1 % to 30.5 % and plastic limit varied from 19.7 % to 22.5 % and Plasticity Index varied from 4.3 to 10.8. Based on the grain size distribution and atterberg's limit, soil samples falls under silty sand classification. In 1925, Sheffield dam, with silty sand foundation failed completely in magnitude of 6.3[11].

In-situ Dry Density and Nominal Moisture Content: From the field data, in-situ dry densities varied from 1.50 to 1.68 gm/cc and nominal moisture content varied from 8.7 to 14.4 percent.

Relative Density test: The maximum density of the sample varied from 1.66 to 1.73 gm/cc and min. density varies from 1.21 to 1.31 gm/cc. Results of RD from maximum and minimum values with respect to in-situ density varied from 50.6% to 79 %.

7.1.2. Cyclic Simple Shear Test

Cyclic Simple Shear test was conducted to evaluate the cyclic strength and liquefaction potential study of sand layer at various depths. Tests were carried out on saturated specimen of dimension 75 mm dia. and 20 mm height. These tests were carried out on soil specimens initially packed at 50 % relative density. Once the sample is packed, all the specimens are then saturated by passing water so as to achieve higher saturation. Specimens are then isotropically consolidated to an effective confining pressure ranging from 1 to 4 kg/cm^2. After the consolidation stage, cyclic shear test was carried out by stress controlled method. A cyclic horizontal shear stress was then applied to the specimen with drainage prohibited. Each specimen was tested with varying cyclic shear stress. The plot obtained for applied cyclic horizontal load, horizontal displacement and pore water pressure of the specimen is recorded as shown in Fig. 10.

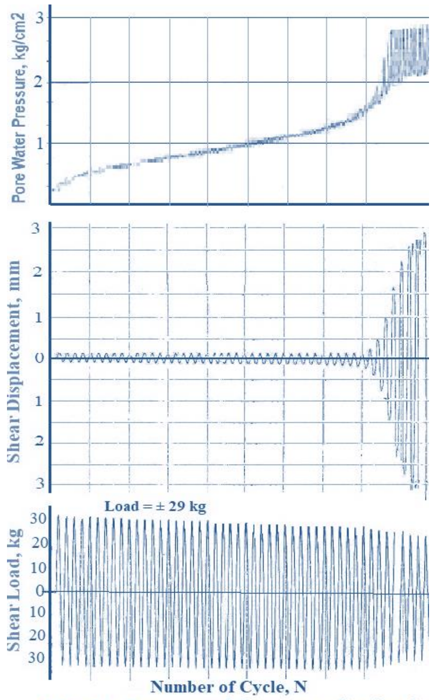


Fig. 10. Test record from a cyclic simple shear test

The number of cycles required to liquefy the soil samples in each case was noted from test plot. Graph is plotted between cyclic resistance ratio (CRR) and number of cycles to initiate liquefaction for samples tested at different confining pressure as shown in Fig 11.

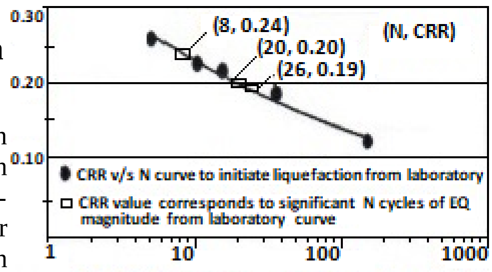


Fig. 11. CRR (σ_v/σ_h) v/s Number of cycles (N)

7.2. Assessment of Liquefaction potential based on DBE

CRR vs. Number of cycle curve as shown in Figure 11 is used to find CRR value with respect to significant number of stress cycles generated or assumed for a particular earthquake magnitude. CRR value is then employed to find out cyclic strength at various depth of soil deposit. Cyclic strength values are compared with the average cyclic shear stresses induced by earthquake motion obtained from seed's simplified method). The detail procedure of simplified method is explained in sec 6.

For the analysis of initial liquefaction, two different magnitudes corresponding to peak ground (horizontal) acceleration (PGA) were adopted as shown in Fig 12. PGA values were considered based on the concept of Design Basis Earthquake (DBE). σ_v/σ_h

Accordingly, stress cycle selected for corresponding earthquake magnitude of 6.5 is 8.0 and for magnitude of 8.0 is 20 [5-6]. The cyclic resistance ratio from laboratory plot corresponding to particular cycle of 8 and 20 is 0.24 and 0.20 respectively.

PGA and stress reduction coefficient is used to find out average cyclic shear stress induced due to ground motion and CCR value from laboratory is used to find out cyclic strength of soil.

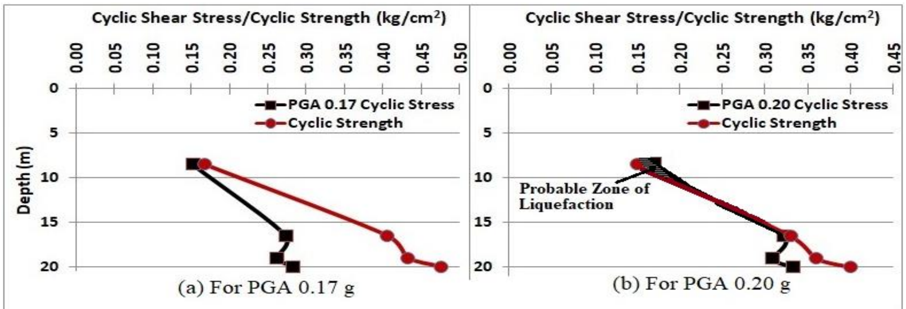


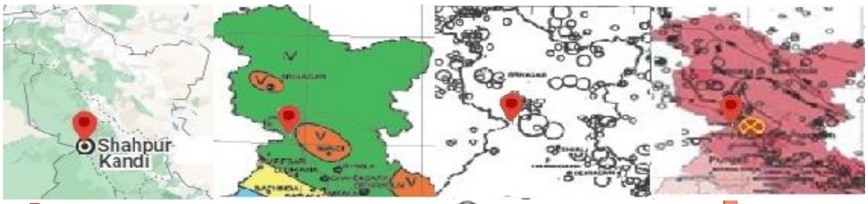
Fig.12. Comparision of cyclic strength with cyclic shear stress

It is observed from the Figure 12 that cyclic strength of soil at different sampling depth is more than the average cyclic shear stresses induced due to PGA of 0.17 g and 0.20 g at respective depths except from 8.5 m to 10.5 m depth at PGA 0.20g. To avoid liquefaction at this depth of foundation near the left abutment, it was suggested to consolidate the foundation, so as to increase the cyclic strength to nullify the liquefaction. However, since the sand deposit is confined by dense boulder material, the effect of liquefaction would be localised.

7.3. Assessing Liquefaction Based on Zone Factor

Following points are considered in assessing the liquefaction potential based on zone factor value of 0.24 g.

1. Location of Shahpurkandi project w.r.t earthquake hazard map falls in the close vicinity of seismic zone V and close to epicentre having earthquake magnitude greater than 8.0 as presented in Figure 14.



Location of Project | Location of project is in Zone 4 (In close vicinity to Zone 5) (IS 1893-2016) | Epicenter > 8.0 (IS 1893-2016) | > 8.0 NDMA website [3]

Fig. 13. Location of the project with respect to Earthquake hazard map

2. PGA value of 0.17 g and 0.20 g (in sub-section 7.2) was considered for analysis with respect to Design Basis Earthquake (DBE) in the year 1992. Subsequently PGA value of 0.31g for Maximum Considered Earthquake (MCE) condition for Shahpurkandi project was approved in National Committee on Seismic Design Parameters (NCSDP) for river valley projects in 2006 [12], considering the seismo-tectonic setup of the region and regional geology.

3. Design horizontal seismic coefficient or PGA was much relied on DBE which was assumed half of Maximum Considered Earthquake (MCE). Both the definition and concept of DBE and MCE which was the design concept in old IS code [13] was dropped in the revised IS 1893-Part 1, 2016 [2].
4. With new revision in 2016, designer is regulated to adopt actual value of A_h from the equation given in code or when the depth of deposit is less than 30 m, then A_h value shall be interpolated between A_h and 0.5 A_h (for depth > 30 m, A_h is half of value obtained from equation).
5. IS code specifies seismic zone factor of 0.24 in zone IV [2] as shown in Table 4.
6. ICOLD, 2018 also specifies PGA value of 0.29 g as a Design Basic Level and PGA 0.54 g as Maximum Credible Level [14].

Table 4. Seismic Zone Factor

	IS 1893-Part 1: 2016			
Seismic Zone Factor (1)	II (2)	III (3)	IV (4)	V (5)
Z	0.10	0.16	0.24	0.36

Examining the above points and considering the importance, benefits (see Table 3) and service life of Shahpurkandi Dam Project in seismic zone, PGA value of 0.24 g is taken to study the liquefaction potential of soil deposits as shown in Figure 14. It is observed from the analysis that all the depths are under the zone of initial liquefaction for higher magnitude > 8.0 and PGA value of 0.24 g.

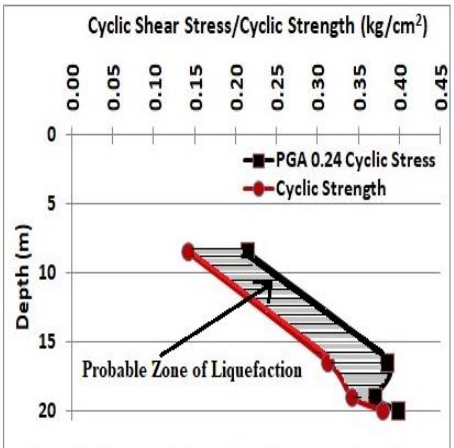


Fig. 14. Comparision of cyclic strength with cyclic shear stress induced (PGA 0.24 g)

8. Conclusion

Seed & Idriss simplified procedure has been used to assess initial liquefaction at various depths of sand deposits at left abutment for Shahpurkandi Dam Project. It is observed that for PGA value of 0.17 g, cyclic strength of soil is more than the induced cyclic shear stress and deposits are not susceptible to liquefaction. For PGA value of 0.20 g, sand deposits are not susceptible to liquefaction except at depth from 8.5 m to 10.5 m where sand lenses are found to liquefy. Based on the analysis made on the higher PGA value of 0.24 g, it is observed that induced stresses are higher than cyclic strength at all depths and sand lenses at 8.5, 16.5, 19 and 20 m are prone to liquefaction. In such cases it is important to treat key location of area with remedial measures so that structure withstands a strong earthquake without any major damages. Suitable measures like providing drainage for release of excess pore water pressure and lowering water table are required to keep the foundation soil free from saturation. In case of loose or unsuitable soil strata in foundation any of the treatment like densification, solidification, soil replacement, strain restraint method etc may be helpful to mitigate the effect of liquefaction. Therefore Assessment of liquefaction potential of foundation soil is important so that essential remedial measure can be taken in advance stage to mitigate its effects.

It is to mention that seismic zonation map has been revised time and again with respect to the actual occurrence of earthquake and damage associated with it, which was underestimated previously (e.g. Koyna, 1967; Killari, 1993; Jabalpur, 1999 and Bhuj, 2001; Strong ground motion in eastern coast area and in A & N). Due to increase in the size of population and urbanization, damage risk from earthquake hazard is much higher even for a moderate magnitude and its after affects could multiply. Therefore design process should guarantee dam safety without any causality in the downstream. Low to moderate earthquake magnitude (M 4.9 to 5.9) may bring instability and distress to dam site which may get unnoticed. Good observation of dam site after the low magnitude earthquake may help in anticipating dam safety at higher magnitude by corrective measures. It is important that observations of PGA record with respect to site specific spectra (from seismic instrumentation) of actual events from the nearby field/dam site are monitored for safety analysis and comparison.

Acknowledgement

Studying the case studies has given additional lessons and awareness related to codes and guidelines for understanding the subject. The authors acknowledges the contributions of the authors in references below whose content have helped to gain knowledge in preparing this technical paper.

References

1. Das, B. M.: Fundamental of Soil Dynamics. Elsevier Science Publishing Co., Inc. New York (1983).
2. IS 1893-Part 1: Criteria for earthquake resistant design of structures. Sixth Revision, Bureau of Indian Standards, New Delhi (2016).
3. NDMA, https://ndma.gov.in/Natural-Hazards/Earthquakes
4. ASTM D 8296: Standard test method for consolidated undrained cyclic direct simple shear test under constant volume with load control or displacement control. ASTM International, PA, United States (2019).
5. Seed, H. B., and Idriss, I., M.: A simplified procedure for evaluating soil liquefaction potential. Earthquake Engineering Research Center, Report No. EERC 70-9, University of California, Berkeley, California (1970).
6. Seed, H. B., and Idriss, I., M.: Ground motions and soil liquefaction during earthquakes. Monograph Series. Earthquake Engineering Research Institute, Berkeley, California(1982).
7. CWC: Accelerated Irrigation Benefit Programme Monitoring Report. Monitoring & Appraisal Directorate, CWC, Chandigarh (2017).
8. PSPCL, https://pspcl.in/Otherlinks/shahpurkandi-dam-project.aspx
9. Hankanadavar, N. P., Kumar, N., Ratnam, M.: Monograph on laboratory determination of dynamics soil properties. CSMRS, New Delhi (2014).
10. Hankanadavar, N. P., Gupta, S. L., Ramakant.: Evaluation of dynamic properties and liquefaction potential of sandy soil. In: International Conference on Advances in Civil Engineering, K.L University, Vijayawada, Andhra Pradesh (2011).
11. Adamo, N., Ansari, N., Sissakian, V., Laue, J., and Knutsson, S.: Dam Safety and Earthquakes. J of Earth Science & Geotech. Engg. Scientific Press Int. Ltd, Vol.10 (6) (2020).
12. NCSDP: Minutes of the XVI meeting of National Committee on Seismic Design Parameters for River Valley Project, NWA, CWC, Pune (2006).
13. IS 1893-Part 1: Criteria for earthquake resistant design of structures. Fifth Revision, Bureau of Indian Standards, New Delhi (2002).
14. ICOLD: International Commission on Large Dams (2018).