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Verification of a new method for evaluation of liquefaction potential analysis

**Abbas Abbaszadeh Shahri · Katayoun Behzadafshar ·
Roshanak Rajablou**

Abstract The seismic response of existing earth dams in
Iran is important after an earthquake both to provide
emergency supplies and to society as well as to ensure
structural safety in engineering terms. Better seismic
capacity of earth dam results in less structural damage and
reduced impacts following an earthquake disaster. Indirect
as well as direct costs following earthquakes have gained
much attention from both the engineering and socioec
onomic research communities in the last few decades. This
study is a valuable tool used to study the response of
geotechnical structures to infrequent or extreme events such
as earthquakes. The Avaj earthquake (2002, Iran) was
applied to a series of model tests which was conducted to
study the response of soil profiles under seismic loading.
The acceleration records at different locations within the
soil bed and at its surface along with the settlement records
at the surface were used to analyze the soil seismic
response. A combination of several software packages with
a generated visual user interface computer code by authors
named as "Abbas Converter" were employed to evaluate
the variation of shear modulus and damping ratio with
shear strain amplitude to assess their effects on site
response. The proposed method was applied to the Korzan
earth dam of Hamedan province in Iran. Site response
analysis using the measured shear wave velocity, estimated
modulus reduction, and damping ratio as input parameters
produced good agreement with the computed site response
in this study.

Keywords Avaj earthquake · Soil behavior · Hamedan
province · "Abbas Converter"

Introduction

On 22 June 2002, at 07:28:20 local time, a destructive
earthquake struck some vast regions in Qazvin, Hamedan,
and Zanjan provinces in Iran. This earthquake was also felt
in Tehran, Kermanshah, Qom, Central, Ardabil, and Giulan
provinces as well as those indicated in Fig. 1.

The magnitude of the earthquake was determined to be
m_b=6.0 by the Geophysics Institute of Tehran University,
M_s=6.0 by the National Earthquake Information Center,
and M_w=6.5 by the US Geological Survey (USGS 2002).
The focal depth of the event, according to the USGS report
(USGS 2002), was approximately 10 km. The main shock
was recorded by 50 accelerograph stations. At a station in
Avaj, 28 km from the epicenter, the maximum horizontal
and vertical accelerations were recorded at approximately
0.5 and 0.26 g, respectively.

The epicenter coordinates of the earthquake was esti-
mated at a point with 48.93 longitude and 35.67 latitude.
As shown in Fig. 2, the fault plane solution (USGS 2002)
indicates that the seismic event occurred on a reverse fault
having a trend at about 115° N.

The focal depth at the beginning of the survey was
announced as 10 km and in further estimations as 5 km.
The earthquake was a low depth one and this can be
considered as one of the reasons for the great damages and
the vastness of the affected areas. The earthquake was

A. Abbaszadeh Shahri (✉) · R. Rajablou
Department of Geophysics, Islamic Azad University,
Hamedan Branch,
Hamedan, Iran
e-mail: a_abbaszadeh@iauh.ac.ir

K. Behzadafshar
Department of Physics, Islamic Azad University,
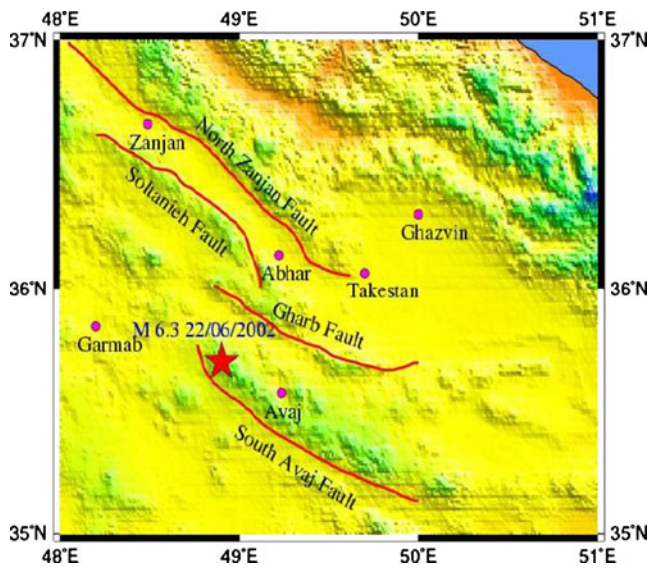Shahr-e-Rey Branch,
Hamedan, Iran

Fig. 1 The location of 2002 Avaj event and its near faults

Fig. 2 The focal mechanism of Avaj earthquake (USGS 2002)

recorded by 65 digital accelerographs installed in different points of the area. The maximum acceleration recorded in this event so far is about 0.5 g at the Avaj station, which is situated 26 km from the earthquake hypocenter. There is no doubt that the acceleration in regions closer to the epicenter of the earthquake is higher than that recorded by the Avaj station and this high acceleration may be regarded as one of the major reasons of destruction and collapse of rural buildings.

The macro-seismic area in Avaj consists of numerous faults and fractures which are of northwest and southeast direction. The epicenter was located at the west and northwest mountains of Avaj area. The macro-seismic area of Avaj earthquake is located in the vicinity of the macro-seismic Buin Zahra earthquake of September 1st, 1962. The Buin Zahra earthquake destroyed completely 91 villages in the area and killed 12,200 persons.
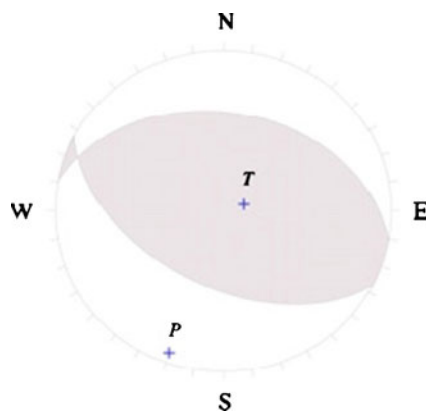
Seismic risk and soil behavior

Evaluating seismic risk in engineering practice is of importance to engineers because, over the years, some of the greatest damage and largest number of human casualties have been caused by severe earthquake. As urbanization continues and more buildings and facilities are constructed, the cost of property damage from future severe earthquakes will escalate.

Much of the damage by earthquakes can be attributed to the behavior of the soils during earthquakes. Large and differential settlements caused by compaction of loose soil, settlement and tilting of structures due to liquefaction of saturated granular soil, and lateral movements of natural slopes have been observed during earthquakes. A more subtle effect of soil conditions on building damage is the influence they have on the characteristics of earthquake ground motions. These characteristics in turn can have an effect on the structural damage that may develop although the foundation soils remain stable.

Seismic site response analysis has been studied extensively over the last few decades. However, available data regarding the dynamic properties and response of soft clay soils subjected to strong seismic shaking have been limited.

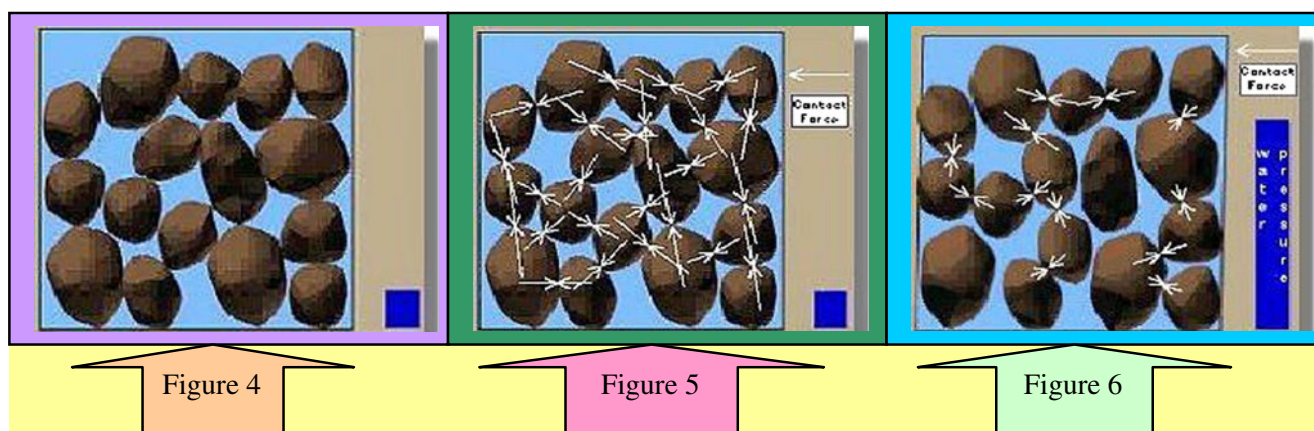**Fig. 3** Main steps to provide a seismic hazard map
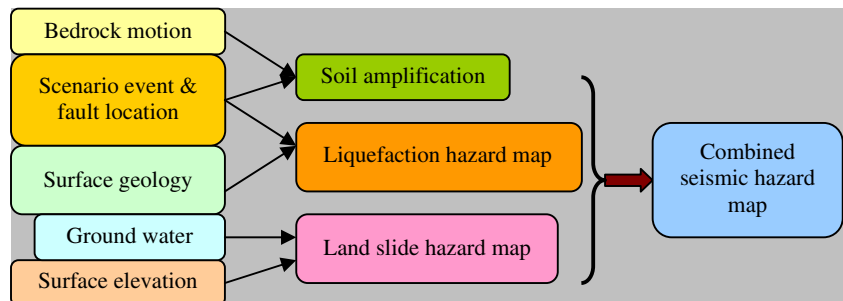
Fig. 4 Typical view of soil grains in an unexcited deposit
Fig. 5 Typical view of soil grains in saturated deposit
Fig. 6 Elevated water pressure created by additional loading

Tiers and Seed (1968) studied the effect of strain level and load cycles on the parameters of the hyperbola model with San Francisco Bay mud. Hardin and Drnevich (1972) carried out a large number of tests and presented empirical equations to evaluate the dynamic modulus and damping ratio of soft clay. Vucetic and Dobry (1991) proposed that the plasticity index (PI) was the key factor influencing the dynamic modulus and damping ratio of both normally consolidated and over-consolidated soils. The normalized dynamic modulus increased and the damping ratio decreased with an increase of the PI. Lanzo et al. (1997) studied the trend of the dynamic modulus and damping ratio under small strains through cyclic simple shear test.

Evaluation of seismic hazard requires a comprehensive investigation of seismic site response known as the effect of local site conditions on earthquake ground motion. Seismic site effect can also be evaluated from shear wave (S wave) velocity profiles (Malagnini et al. 1993; Milana et al. 1996; Nguyen et al. 2004) that are obtained through borehole measurements or seismic refraction and/or reflection methods. Boreholes are usually limited in number, measurements are expensive and time consuming, and the obtained velocities may not be representative of the entire study site. Seismic refraction and reflection methods, on the other hand, may be problematic in urban conditions. Some of the difficulties are:

- Generally, signal-to-noise ratio is significantly low because of high background seismic noise and small seismic energy sources used in urban areas.
- Setting up long seismic profiles is generally difficult if not impossible.
- The effective transmission of seismic energy to greater depths is limited due to high levels of attenuation in soft sediments. Active surface wave methods have been extensively used to obtain S wave velocity profiles.

As indicated in Fig. 3, in the regional seismic loss estimation analysis, it is considered necessary to determine the bedrock motion in the region. The most common method involves the use of an empirical attenuation relationship. These relationships communicate a given ground motion parameter in a region as function of the size and location of an earthquake event. Applying statistical regression analyses to recorded data, numerous relationships had been developed in the past. Often these relationships are developed with different functional forms and with different definitions of ground motion, magnitude, distance, and site conditions.

All these types of behavior are influenced by the intensity of earthquake shaking. Thus, a determination of seismic risk for a particular facility must include an evaluation of the earthquake ground motions that are likely to be induced by future earthquakes at the site. To evaluate these ground motions, knowledge is needed of the following key elements:

1. Possible seismic sources
2. Size and frequency content of the possible earthquake
3. Distance and orientation of each seismic source with respect to the site

Once these geologic and seismologic inputs are determined, seismic hazard of a site can be evaluated. In engineering practice, these steps for evaluating the hazard and then calculating the risk are done in varying degree of detail depending on the importance of the facility and the consequences of the risk.

Liquefaction phenomena

Liquefaction of fill in the dam may occur. Liquefaction is the large drop in stiffness and strength of soil due to seismic

movements (Byrne and SeidKarbasi 2003). As a result, part of a dam may slump and slides off the structure. Liquefaction is the most important cause of instability of earth embankments during earthquakes and may cause large deformation, loss of capacities, and even complete failures. Liquefaction is initiated when cyclic ground motions causes

loose soil particles to attempt to rearrange into a denser configuration. The rapid nature of the loading of the saturated soil results in an undrained condition, and the soil particles cause an increase in excess pore pressures as they try to densify. The increasing pore pressures lead to a drop in effective stress and, eventually, soil liquefaction.
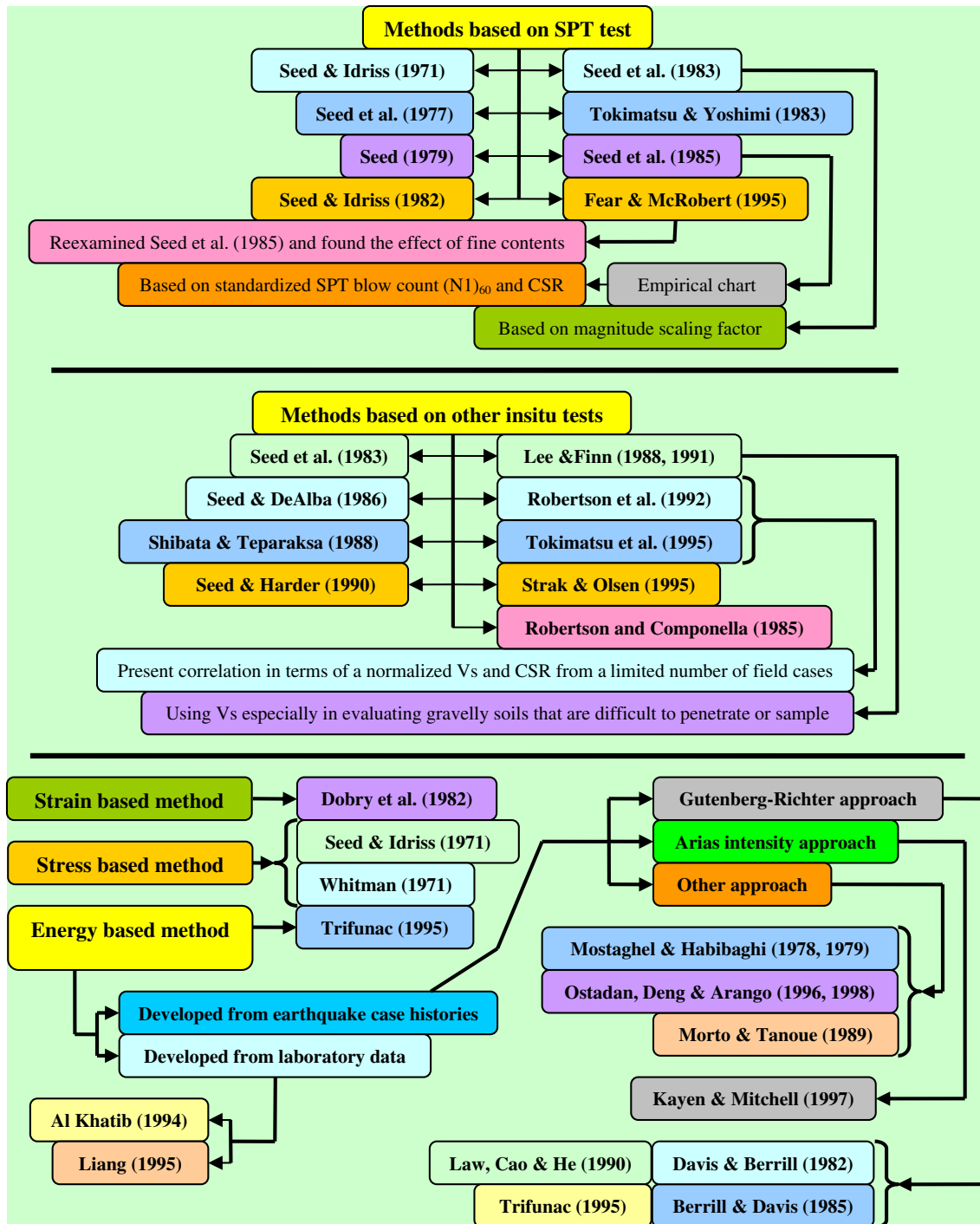

Fig. 7 Available methods for evaluation of liquefaction

Table 1 Drilled boreholes in site of Korzan earth dam

| Borehole	Depth (m)	Location	GWT (m)
Kor-1	60	Right support	20
Kor-2	58.2	Upstream of the river	3.8
Kor-3	80	Axis of dam	7.8
Kor-4	72	Axis of dam	12.4
Kor-5	44.6	Left support	-
Kor-6	30	Downstream of the river	-
Kor-7	31	Upstream of the river	8.45
Kor-8	35	Downstream of the river	-
Kor-9	50	Axis of dam	1.30
Kor-10	69	Axis of dam	7.30
Kor-11	40	Upstream of the river	11

Figures 4 and 5 show a typical view of soil grains in an unexcited, saturated deposit. The blue column on the right indicates the magnitude of pore water pressure present. The arrows in Fig. 5 indicate the forces created by the interactions of the soil grains. Figure 6 shows elevated water pressure created by additional loading as from a seismic event. The increased water pressure allows the grains to "float" thereby decreasing the interaction between grains and thus causing the characteristic properties of liquefaction (http://www.ce.washington.edu/~liquefaction/html/main.html).

Liquefaction analysis methods

The study of liquefaction is a rapidly growing subject in the field of geotechnical earthquake engineering. Analysis involves an evaluation of a site's susceptibility to liquefaction, an understanding of the conditions for initiation of liquefaction, and a prediction of the effects of liquefaction. As shown in Fig. 7, several methods of predicting liquefaction initiation and its effects on a site's earthquake response are available to geotechnical engineers.

Soils susceptible to liquefaction consist of saturated, loosely deposited, shallow, uniform sands. They can be produced naturally by processes that form fluvial or saturated colluvial and aeolian deposits, or they can be manmade, resulting from poorly compacted fill or hydraulic fill.
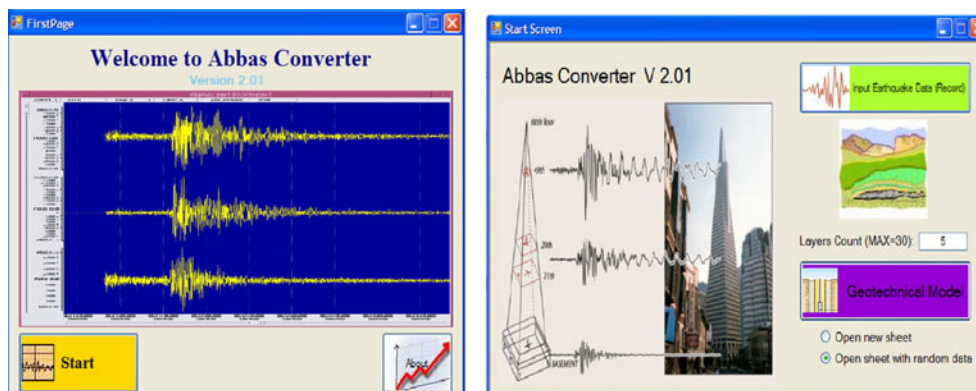
Testing program

Most of the early constructed dams in Iran were built with no consideration of earthquakes and were not designed for earthquake forces because designers did not consider earthquakes probable threats. As more information of earthquakes was collected, the need to built dams that could withstand earthquakes was recognized. Earth embankment dams may be damaged by earthquakes in several ways including dam movement, liquefaction of fill in a dam, water waves caused by an earthquake over topping a dam, and direct damage caused by a dam being located on a fault.

The Korzan earth dam is located on the Korzan river in the south west of Hamedan province, Iran, with a 2-km distance from Korzan village which has an 8-km distance from Touyserkan city. The site of the dam is located at 34° 34′20″ to 34°35′ north latitude and 48°20′to 48°23′10″ east longitude. This earth dam has a 43 m height from the river bed, 1,428 m crest line length, and 34 Mm^3 reservoir capacity. Necessary soil data were collected from field investigations, different relevant sources of the target area, and accumulated in Microsoft Excel. A total of 11 boreholes as enumerated in Table 1 with SPT data were collected from different organizations and used to study site amplification and soil liquefaction potential characteristics of the area.

In order to increase the accuracy of the study and take over the encountered problems, the author would be forced to generate the "Abbas Converter" (Abbaszadeh Shahri et al. 2009). This computer code is generated in two versions 1.01 and 2.01. The 2.01 version such as the previous one has a geotechnical platform with a moderate range of earthquake engineering applications but improved for liquefaction analysis. It includes a geotechnical model, which is used in this study to model the liquefaction of idealized soil profile of the studied region. This part is defined by several geotechnical parameters, as well as some constitutive parameters to describe the soil's behavior. The start screen of this code is shown in Fig. 8. The results of these trials

Fig. 8 The generated computer code by authors

were compared with existing field and laboratory relationships, and appropriate adjustments were made to the model parameters.

After calibrating its input parameters, the constructed model was used together with employed software packages to obtain the response of a layered soil profile. The main
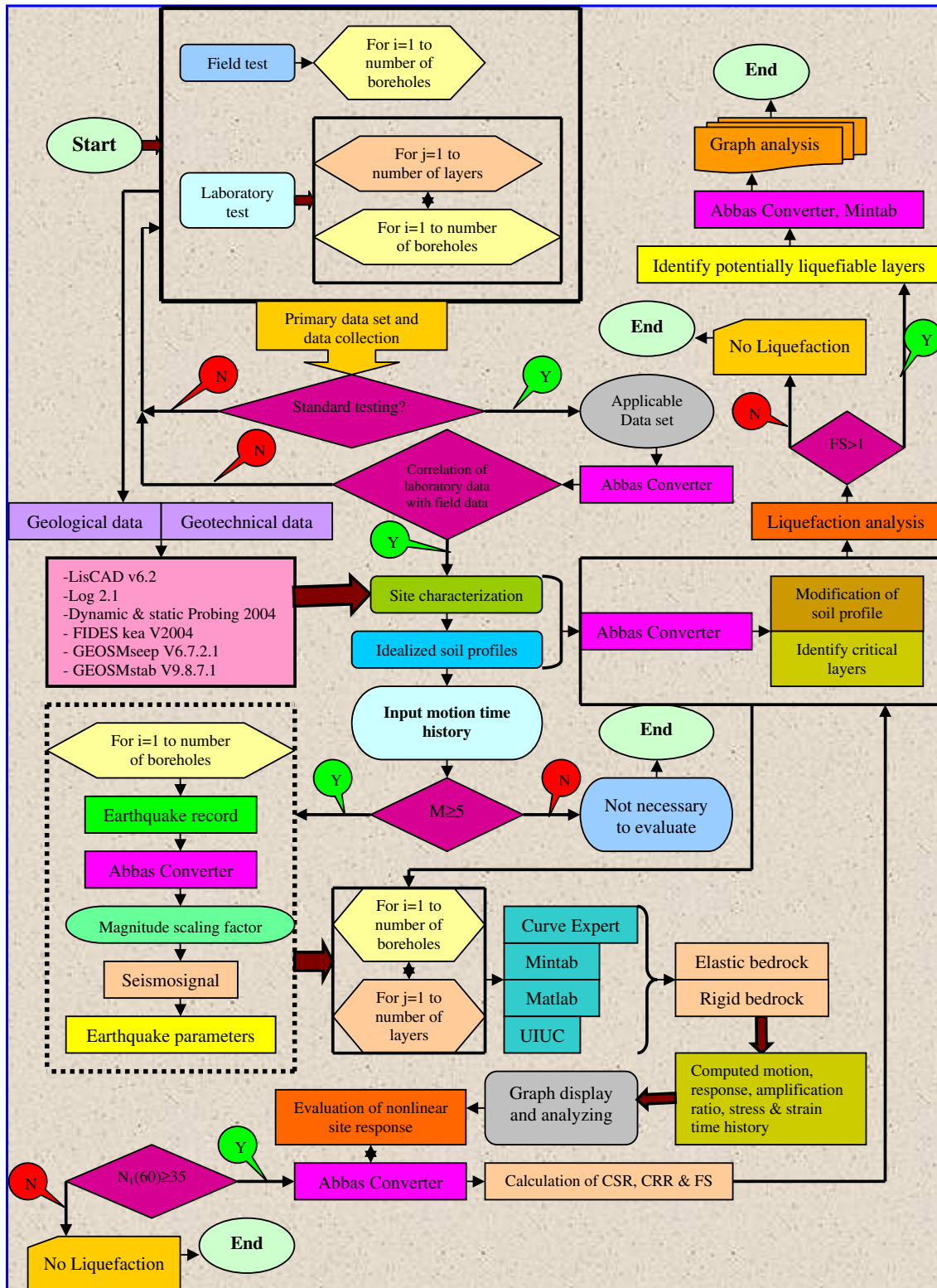

Fig. 9 Proposed flowchart of this study

Table 2 Characteristics of the idealized soil profile

Depth (m)	USCS	SPT	Fine Content (%)	Vs (m/s)
2	CL	7	59	218.62
4	CL-ML	14	53	262.367
6.5	SP-SC	19	49	237.396
8.5	CL	5	61	288.129
10.7	CL	13	51	257.333
12.5	SP-SC	16	23	232.365
15	SP-SM	27	20	275.498
17.8	SW-SM	33	30	300.034
20.5	SW-SM	50	35	358.262
22.8	CL	21	64	284.752
25.5	SW-SM	45	22	342.457
Bedrock, Vs=1679m/s				

goal of this phase of the study was to evaluate the "Abbas Converter's" capabilities in response of liquefiable soils. The initial evaluation consisted of a comparison of "Abbas Converter" results to those of existing methods and programs.

In reference to Fig. 9, which shows the flowchart of the study, the experimental estimation of ground motion can be carried out using earthquake data, in areas having a sufficient seismicity and an adequate coverage of recording stations. In order to evaluate the effect of particular geological conditions on the change of the local seismic response of ground motion, geophysical surveys were performed for the lithotypes with a significant extent in the territory. Using the results obtained in different geophysical measurements, average shear wave velocities of surface soils in the uppermost 30 m of soil were determined.

Previous studies on ground motion behavior (Medvedev 1962; Joyner and Fumal 1984; Borcherdt et al. 1991) have revealed a correlation between this average shear wave velocity and the site amplification factor. Additionally in the present paper, the dependence on local soil instability conditions related to mechanical characteristics of surface soils, such as the slope of soils and the depth of groundwater table, was taken into account.

Data and results

On base of field and laboratory tests, the optimized and idealized soil profile for the studied area was proposed in Table 2. The representative available boring is up to a depth of 80 m. Based on the knowledge that groundwater level changes with the season, groundwater table in this region is considered to be at a depth of −1.3 to −20 m (Fig. 9); to prove the validation of the proposed method, the obtained result while taking into account the fine correction factor, were compared with the previously proposed procedures by Liao and Whitman (1986), Liao et al. (1988), Seed and

Idriss (1982), Golesorkhi (1989), Blake (1997), Strak and Olsen (1995), and Idriss (1997). The L Component of the Avaj earthquake (2002, Iran) which is recorded in Asada bad station of the Hamedan province after the baseline correction by consideration of rigid and elastic bedrock was applied to the investigated site and the computed response on the surface were determined as indicated in Fig. 10. To analyze the liquefaction potential of the region subjected to applied earthquake, a comparison between input and computed stress time histories were executed and shown in Fig. 10, respectively. To verify the applied method in this study, a comprehensive comparison between the liquefaction resistance factors, safety factor, shear modulus reduction curve, and damping ratio curves were performed for the soil profile, and the resulting liquefaction potential, for this area was estimated and showed in Fig. 11. The computed strain and PGA for various conditions were plotted in Fig. 11, respectively. By using this method, the spectral acceleration and amplification ratio for the assumed conditions were at last computed by "Abbas Converter" and shown in Fig. 12. The numerical analysis of this study for main parameters which is computed by the designed code was pointed in Tables 3 and 4.

Discussion and conclusions

A spectral analysis of the results showed that the stiffness of the soil deposits had a significant effect on the characteristics of the input motions and the overall behavior of the structure. The peak surface acceleration measured by the proposed method was significantly amplified, especially for low amplitude base acceleration. The amplification of the earthquake shaking as well as the frequency of the response spectra decreased with increasing earthquake intensity. The results clearly demonstrate that the layering system has to be considered, and not just the average shear wave velocity, when evaluating the local site effects.

The results of this study indicate that the generated program "Abbas Converter" is becoming a reliable tool for site response analysis. Comparison of the site response analysis of a proposed profile agreed good reasonable matching by the known applicable procedures. This study shows that the proposed method can be used for site response analysis as well as the other procedures.

Result of the liquefaction potential presented in this study subjected to Avaj earthquake shows that by a greater earthquake the layers 1, 4, and 6 are susceptible and may show the liquefaction behavior. This study showed that the studied area have low and moderately low liquefaction potential, to Avaj event.
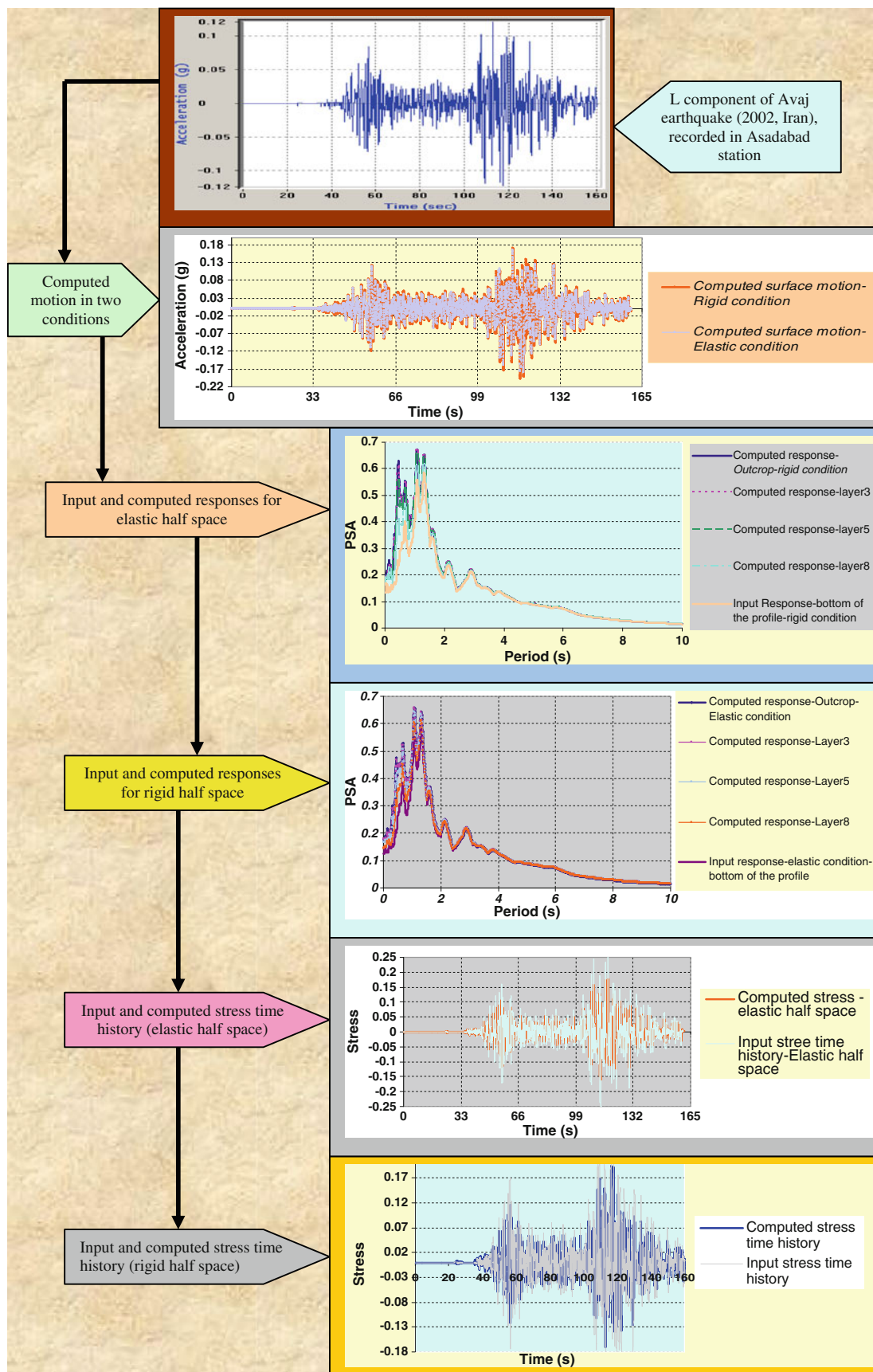
Fig. 10 Comparison between input and computed parameters in various conditions of bedrock
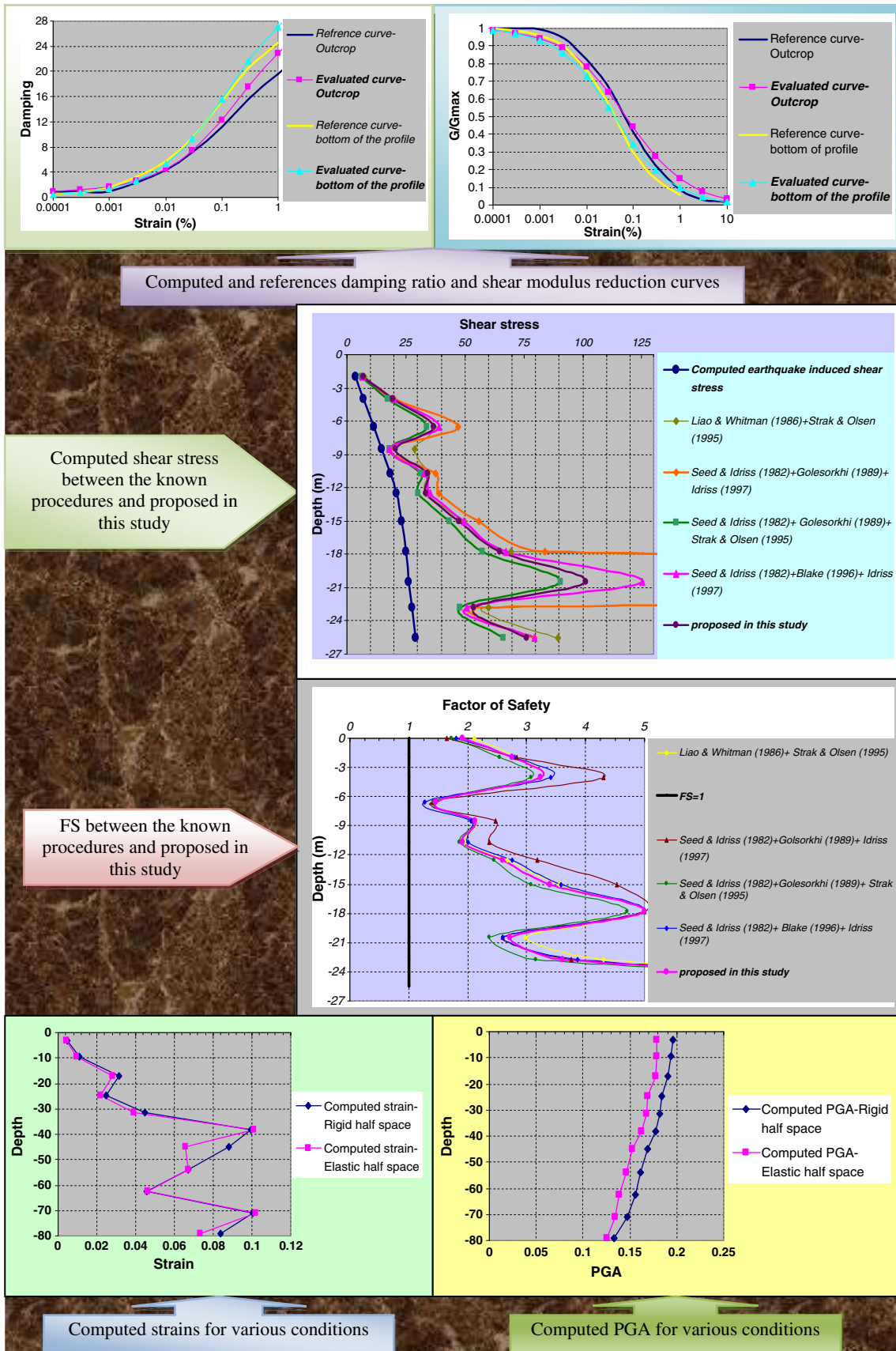
Fig. 11 Comparison of the computed values by proposed method with other procedures

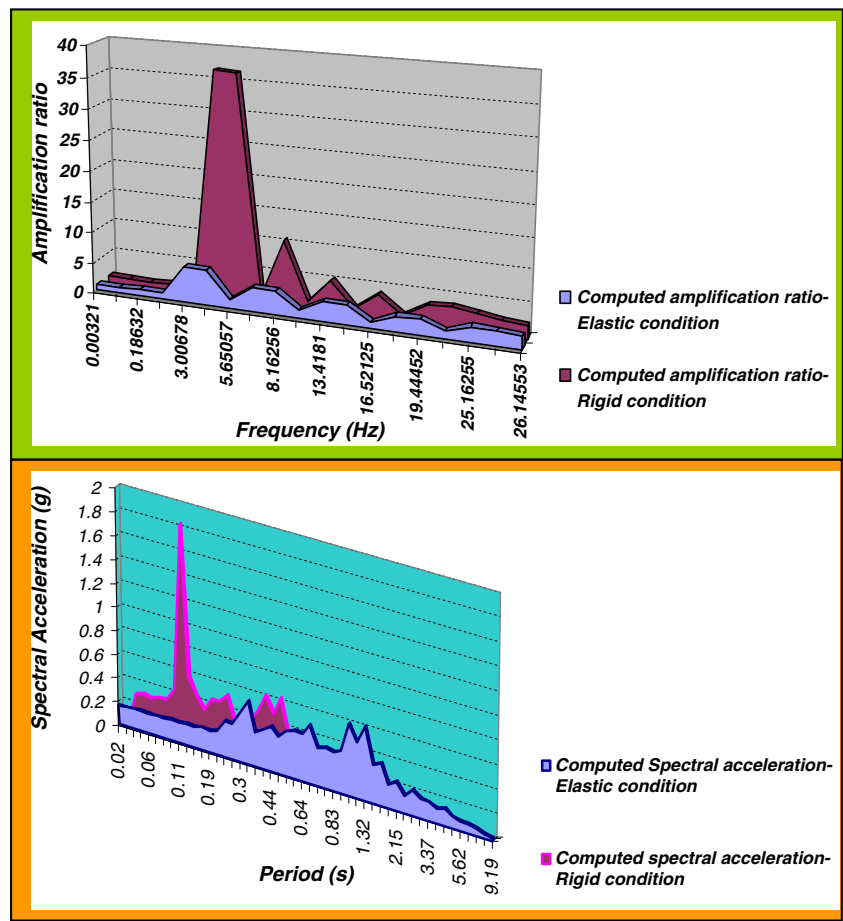**Fig. 12** Computed spectral acceleration and amplification ratio

Table 3 Numerical results of the study

Parameter	Condition	Computed maximum value at…
Input motion	Elastic	0.125 g (113.1 s)
	Rigid	−0.1335 g (117.6 s)
Computed motion	Elastic	−0.1785 g (117.6 s)
	Rigid	−0.1958 g (116.2 s)
Input response	Elastic	0.581 g (1.32 s)
	Rigid	0.585 g (1.32 s)
Computed response	Elastic	0.660 g (1.08 s)
	Rigid	0.674 g (1.08 s)
Amplification ratio	Elastic	5.80 (3.0357 Hz)
	Rigid	36.7 (3.0228 Hz)
Spectral acceleration	Elastic	0.617 g (1.32 s)
	Rigid	1.822 g (0.33 s)
Input stress	Elastic	0.250 (117.6 s)
	Rigid	0.274 (117.6 s)
Computed stress	Elastic	0.1784 (117.6 s)
	Rigid	0.1935 (116.2 s)
Input strain	Elastic	0.0734% (117.6 s)
	Rigid	0.0833% (117.6 s)
Computed strain	Elastic	0.00434% (117.6 s)
	Rigid	0.00465% (116.2 s)
Computed PGA	Elastic	0.1785 g (surface)
	Rigid	0.1958 g (surface)

Table 4 computed values by use of "Abbas Converter"

Depth (m)	σ_{v0}	r_d	τ_{cyc}	$N_1 (60)$	CSR_L	σ'_{v0}	$\tau_{cyc, L}$	FS_L	C_N
2	31.14	0.983	5.365	16.867	0.22	31.14	6.82	1.91	1.757
4	62.27	0.966	7.032	22.32	0.31	62.27	19.34	2.75	1.24
6.5	101.2	0.95	11.404	23.16	0.36	101.2	36.95	3.24	0.965
8.5	134.48	0.94	14.212	20.342	0.16	129.74	20.75	1.46	0.8476
10.7	175.487	0.916	16.174	4.888	0.22	155.86	34.289	2.12	0.748
12.5	209.04	0.883	17.628	14.8759	0.19	177.22	33.67	1.91	0.6887
15	255.63	0.799	18.373	18.765	0.23	206.90	47.587	2.59	0.6255
17.8	307.82	0.716	19.123	20.5884	0.27	240.14	64.83	3.39	0.5719
20.5	358.15	0.642	20.235	31.884	0.38	266.25	101.175	5	0.5314
22.8	401.02	0.608	19.892	12.072	0.18	299.49	53.908	2.71	0.5030
25.5	451.34	0.566	21.121	25.6392	0.23	331.53	76.25	3.61	0.4748

References

Abbaszadeh Shahri A, Esfandiyari B, Hamzeloo H (2009) Evaluation of a nonlinear seismic geotechnical site response analysis method subjected to earthquake vibrations (case study: Kerman province, Iran). Arab J Geosci (in press)

Alkhatib M (1994) Liquefaction assessment by strain energy approach. Ph.D. thesis (T. Kagawa, advisor), Wayne State University. p 212

Berrill JB, Davis RO (1985) Energy dissipation and seismic liquefaction of sands: revised model. Soils Found 25(2):106–118

Blake TF (1997) Formula (4). In: Youd TL and Idriss IM (eds) Summary Report of proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils. Technical report. NCEER 97-0022

Borcherdt RD, Wentworth CM, Janssen A et al. (1991). Methodology for predictive GIS mapping for special study zones for strong ground shaking in the San Francisco Bay Region. In: Proceedings of the fourth international conference on seismic zonation, 3. pp 545–552

Byrne MP, SeidKarbasi M (2003) Seismic stability of impoundments. In: 17th Annual Symposium, Vancouver Geotechnical Society

Davis RO, Berrill JB (1982) Energy dissipation and seismic liquefaction in sands. Earthquake Eng Struct Dyn 10:59–68

Dobry R, Ladd RS, Yokel RM et al. (1982) Prediction of pore water pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method. NBS Building Science Series 138, US Department of Commerce. p 152

Fear CE, McRoberts EC (1995) Report on liquefaction potential and catalogue of case record. Internal research report. Geotechnical Engineering Library, Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada, p 338

Finn WDL (1988) Dynamic analysis in geotechnical engineering. In: Proceedings, earthquake engineering and soil dynamics II—recent advances in ground motion evaluations. Geotechnical special publication 20, ASCE. pp 523–591

Finn WDL (1993) Evaluation of liquefaction potential. In: Proceedings of the conference on soil dynamics and geotechnical earthquake engineering, Balkema, Rotterdam, 1993

Golesorkhi R (1989) Factors influencing the computational determination of earthquake-induced shear stresses in sandy soils. Dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy, University of California at Berkeley

Hardin BO, Drnevich VP (1972) Shear modulus and damping in soil: design equations and curves. J Soil Mech Found Eng Div ASCE 98(7):667–692

Idriss IM (1997) Evaluation of liquefaction potential and consequences: historical perspective and updated procedures. Presentation notes, 3rd short course on evaluation and mitigation of earthquake induced liquefaction hazards, San Francisco, March 13–14. p 16

Joyner WB, Fumal T (1984) Use of measured shear-wave velocity for predicting geological site effect on strong motion. In: Proceedings of eighth world conference on earthquake engineering, 2. pp 777–783

Kayen RE, Mitchell JK (1997) Assessment of liquefaction potential during earthquakes by arias intensity. J Geotech Geoenviron Eng 123(12):1162–1174

Lanzo G, Vucetic M, Doroudian M (1997) Reduction of shear modulus at small strains in simple shear. J Geotech Geoenviron Eng ASCE 123(11):1035–1042

Law KT, Cao YL, He GN (1990) An energy approach for assessing seismic liquefaction potential. Can Geotech J 27(3):320–329

Lee MKW, Finn WDL (1991) DESRA-2C: dynamic effective stress response analysis of soil deposits with energy transmitting boundary including assessment of liquefaction potential. The University of British Columbia, Faculty of Applied Science, Vancouver

Liang L (1995) Development of an energy method for evaluating the liquefaction potential of soil deposit. Ph.D. dissertation (J.L. Figueroa and A.S. Saada, advisors), Case Western Reverse University. p 281

Liao SSC, Whitman RV (1986) Catalogue of liquefaction and non-liquefaction occurrences during earthquakes. Research report, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge

Liao SSC, Veneziano D, Whitman RV (1988) Regression models for evaluating liquefaction probability. J Geotech Eng 114(4):389–411

Malagnini L, Rovelli A, Hough SE, Seeber L (1993) Site amplification estimates in the Garigliano Valley, Central Italy, based on dense array measurements of ambient noise. Bull Seismol Soc Am 83:1744–1755

Medvedev J (1962) Engineering Seismology. Academia Nauk Press, Moscow, 260

Milana G, Barba S, Del Pezzo E, Zambonelli E (1996) Site response from ambient noise measurements: new perspectives from an array study in Central Italy. Bull Seismol Soc Am 86:320–328

Moroto N, Tanoue Y (1989) Liquefaction potential of sandy ground from an energy consideration. In: Proceeding of 4th international conference on soil dynamics and earthquake engineering, Computational Mechanics Publications, South Hampton, UK. pp 22–25

Mostaghel M, Habibaghi K (1978) Cyclic liquefaction strength of sands. Report, School of Engineering, Pahlavi University, Shiraz, Iran. p 25

Mostaghel M, Habibaghi K (1979) Cyclic liquefaction strength of sands. Earthquake Eng Struct Dyn 7:213–233

Nguyen F, Van Rompaey G, Teerlynck H, Van Camp M, Jongmans D, Camelbeeck T (2004) Use of microtremor measurement for assessing site effects in Northern Belgiuminterpretation of the observed intensity during theMs=5.0 June 11 1938 earthquake. J Seismol 8:41–56

Ostadan F, Deng N, Arango I (1996) Energy-based method for liquefaction potential evaluation, phase1—feasibility study. U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology, Building and fire Research Laboratory

Ostadan F, Deng N, Arango I (1998) Energy-based method for liquefaction potential evaluation. In: Proceeding: eleventh European conference on earthquake engineering, Sept. pp 6–11

Robertson PK, Campanella RG (1985) Liquefaction of sands using the CPT. J Geotech Eng Division ASCE 111(GT3):384–403

Robertson PK, Woeller DJ, Finn WDL (1992) Seismic cone penetration test for evaluating liquefaction potential under cyclic loading. Can Geotech J 29(4):686–695

Seed HB (1979) Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. J Geotech Eng Div ASCE 105 (GT2):201–255

Seed HB, Booker JR (1977) Stabilization of potentially liquefiable sand deposits. J Geotech Eng Div ASCE 103(GT7):757–768

Seed HB, De Alba P (1986) Use of SPT and CPT test for evaluating the liquefaction resistance of soils. In: Proceedings in situ 1986, ASCE

Seed RB, Harder LF (1990) SPT-based analysis of cyclic pore pressure generation and undrained residual strength. In: Proceedings of the H.B. Seed Memorial Symposium, 2. Bi-Tech Publishing Ltd., Berkeley. pp 351–376

Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. J Soil Mech Found Div ASCE 97 (SM9):1249–1273

Seed, H.B. and Idriss, I.M., (1982). Ground motions and soil liquefaction during earthquakes. Earthquake Engineering Research Institute, Oakland, California, Monograph Series, 134

Seed HB, Arango I, Idriss IM (1983) Evaluation of liquefaction potential using field performance data. J Geotech Eng Div ASCE 109(3):458–482

Seed HB, Tokimatsu K, Harder LF, Chung RM (1985) Influence of SPT procedures in soil liquefaction resistance evaluations. J Geotech Eng Division ASCE 111(12):1425–1445

Seed HB, Wong RT, Idriss IM, Tokimatsu K (1986) Moduli and damping factors for dynamic analyses of cohesionless soils. J Geotech Eng 112(GT11):1016–1032

Shibata T, Teparaksa V (1988) Evaluation of liquefaction potentials of soils using cone penetration tests. Soil Found 28(2):49–60

Strak TD, Olsen SM (1995) Liquefaction resistance using CPT and field case histories. J Geotech Eng 121(12):856–869

Tiers GR, Seed HB (1968) Cyclic stress–strain characteristics of clay. J Soil Mech Found Eng Div ASCE 94(2):555–569

Tokimatsu K, Yoshimi Y (1983) Empirical correlation ship of soil liquefaction based on NSPT value and fines content. Soil Found JSSMFE 23(4):56–74

Tokimatsu K, Taya Y and Kubota Y (1995) Correlation between CPT data and dynamic properties of in situ frozen samples. In: Proceedings, third international conference on recent advances in geotechnical earthquake engineering and soil dynamics, vol. I, St. Louis, Missouri, August

Trifunac MD (1995) Empirical criteria for liquefaction in sands via standard penetration tests and seismic wave energy. Soil Dyn Earthquake Eng 14:419–426

USGS (2002). Available at: http://www.usgs.gov

Vucetic M, Dobry R (1991) Effect of soil plasticity on cyclic response. J Geotech Eng ASCE 117(1):89–107

Whitman RV (1971) Resistance of soil to liquefaction and settlement. Soils Found 11(4):59–68