Effect of Liquefaction on Displacement Spectra

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ABSTRACT :

At present, the seismic design of structures is mainly based on the response spectra. The seismic responses for the deep foundations, the underground structures and structures with the long or high scale are dominated by soil deformation in general and in these cases, the displacement spectra is more significant than the acceleration spectra. Liquefaction is one of the important reasons for earthquake damages. The liquefied soils filter the high frequency parts of incident waves and while amplify the low frequency parts. The later effects are quite significant to the seismic design of above structures and little study, however, is conducted for the problem.
The effect of liquefied soil layers on displacement spectra is discussed and the revised displacement spectra due to liquefaction are presented in the paper. The effects of liquefaction on the peaks of surface displacements, different frequency range of spectra and the regularity of the surface ground motion are investigated by seismic record analysis, numerical simulation and shaking table tests. The decreasing and increasing threshold of liquefaction are identified and the revised form of displacement spectra is constructed. The results here indicate: (1) For the uniform incidence of equal-amplitude, the liquefied soil layer amplifies the displacement amplitudes by 5 times to 25 times; (2) For the random seismic incidence, the liquefied soil layer enlarges the displacement amplitudes by a few times compared with the non-liquefied soil layer; (3) The amplification of the displacement spectra due to liquefaction begins at 1s and the most notable range is 2s-5s; (3) The amplification of the displacement spectra due to liquefaction is 0.1m-0.7m and increases with the increasing of intensity of the inputting waves.

KEYWORDS: Liquefaction, Soil Layer; Displacement Spectra; Revised Displacement Spectra

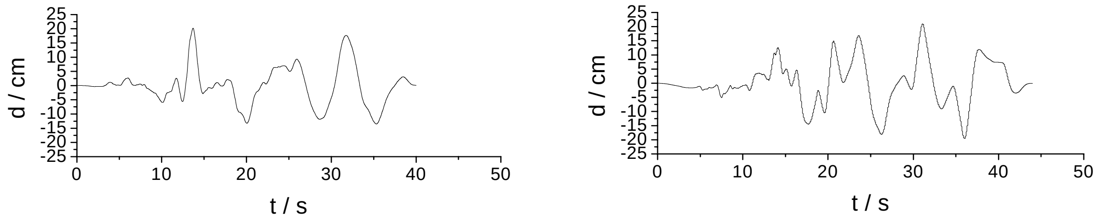
1. INTRUDUCTION

For foundation and underground structure, it is more important to analyze soil displacement than study acceleration. Because the damage of the foundation and underground structure in soft site is mainly controlled by soil displacement. The soil displacement is divided to performance displacement and cyclic displacement. For performance displacement, many subjects have been studied. But for cyclic displacement, it has not been studied yet.
In this study, the effect of liquefied soil layers on displacement spectra is discussed and the revised displacement spectra due to liquefaction are presented in the paper. The effects of liquefaction on the peaks of surface displacements, different frequency range of spectra and the regularity of the surface ground motion are investigated by seismic record analysis and numerical simulation.

2. ANALYSIS FOR EARTHQUAKE RECORDS

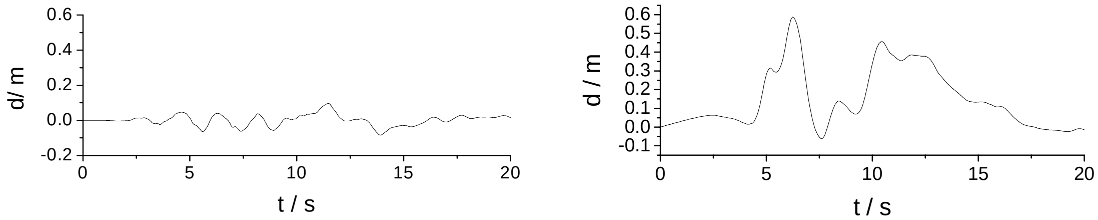
The displacement history on liquefaction and non-liquefaction site in 1987 Superstition Hills Earthquake and 1995 Kobe Earthquake is shown in Fig.1 and Fig.2 and the liquefaction occurred at 15s and 4s respectively. It can be seen that the displacement, which is most low frequency on the liquefaction site, is bigger than that on non-liquefied site after liquefaction.
The displacement response spectra on liquefaction and non-liquefaction site are shown in fig.3. The figure shows that

the displacement in the range of 3-4s is magnified greatly. Then the increase of displacement response spectra on liquefaction and non-liquefaction sites in two earthquakes is averaged and shown in fig.4. It is an average result of effect of liquefaction on displacement spectra on earthquake site. It can be seen that the displacement response spectra is enlarged 0.2m-0.6m in the range of 2s-5s.



(a) non-liquefaction site (b) liquefaction site

Figure 1 Displacement time history records on liquefaction and non-liquefaction site in 1987 Superstition Hills Earthquake



(a) non-liquefaction site (b) liquefaction site

Figure 2 Displacement time history records on liquefaction and non-liquefaction site in 1995 Kobe Earthquake

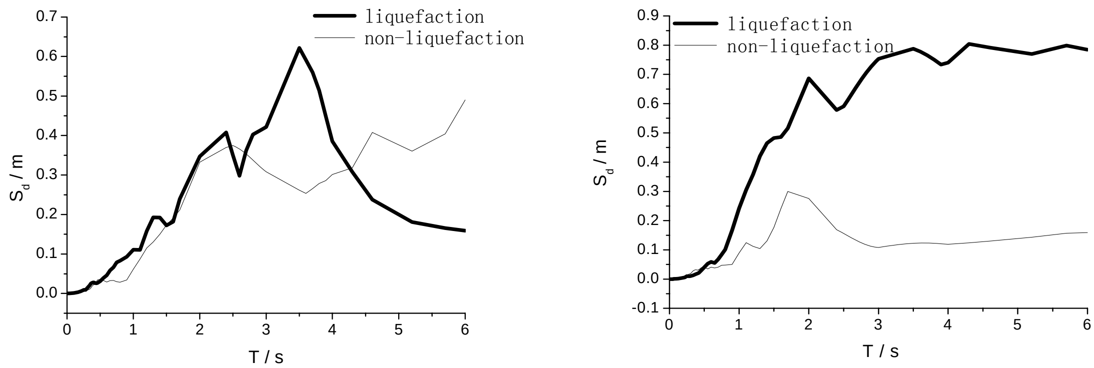


Figure 3 Displacement response spectrum on liquefaction site and non-liquefaction site

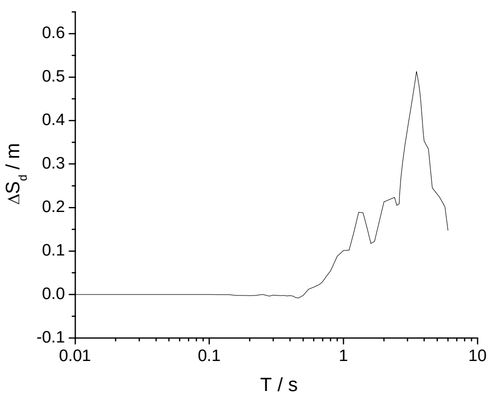


Figure 4 Liquefaction-increment displacement response spectrum

3. NUMERICAL SIMULATION

The best way to learn the difference in surface ground motion brought by liquefaction is to make comparison between the records on the liquefied site and these on its adjacent non-liquefied site. However, this ideal condition doesn't exist at present. Numerical simulation by existing theory may solve the problem partly since the surface motion both on the liquefied site and on the non-liquefied site can be obtained simultaneously.

3.1 Analytical Method and Procedure

3.1.1 Method

Considering a soil layer subjected to an upward shear wave, one-dimensional effective stress method is used in the analysis. The iterative procedure is employed to simulate the nonlinear behavior of soil (Sun and Yuan, 2004). In estimating the ground motion history on liquefiable sites, the increment of pore pressure is calculated by the cycle-by-cycle formula (Sun *et al*, 2005).

3.1.2 Procedure

(1) The soil layer is considered as a one-dimensional horizontal shear motion. (2) Three recorded seismic waves are used as input motions from the bedrock. (3) The surface acceleration and response spectrum for the fully clayey profile are calculated. (4) The surface acceleration and response spectrum for the same profile but with a sand layer are calculated. (5) The difference of surface acceleration histories and response spectra between two cases of above (3) and (4) is investigated for different profiles and different input motions.

3.1.3 Input Waves and Soil Profiles

The standard design response spectrum used in the paper is shown in Fig.5, in which $T_{g,s}$ is the standard characteristic period. According to Chinese Aseismic Code [7], the standard characteristic period $T_{g,s}$ is 0.35s, 0.45s and 0.65s for type Ⅱ, type Ⅲ, and type Ⅳ sites, respectively. The $A_{\max,s}$ is 0.08g, 0.16g and 0.32g for the earthquake intensities of 7, 8 and 9, respectively.

Considering the soil layer as a fully clayey site, three artificial seismic acceleration waves are obtained from the standard response spectrum and then are inverted to the bedrock to be taken as input waves. Three artificial seismic waves on the bedrock are presented in Fig. 6 and named as AW1, AW2 and AW3, respectively. Also, three recorded seismic waves are used as input waves from the bedrock, which are showed in Fig. 7 and named as RW1, RW2 and RW3, respectively. RW1 is the El-Centro wave recorded in the Imperial Valley Earthquake of United State of America in 1940. RW2 is acceleration record at Qianan during aftershock of the Tangshan Earthquake of China in 1976 and RW3 is the acceleration record at Beijing Hotel during the Tangshan Earthquake of China in 1976. In addition, RW3 is the wave of vibration type and, RW1and RW2 are the waves of shock type.

In the analysis, two typical types of profiles are employed. One is a non-liquefaction site with fully clayey soil layer and the other is a site with a sand layer with potential liquefaction. The depth of the both profiles is 30m and water elevation is 2m. The velocity distribution of the profile is $v_s = 130 + 3.75h$ and the equivalent shear wave velocity v_{se} is 170m/s, which represents a site of Ⅱ type. In the profile with sand soil, the thickness of sand layer are 2m, 4m, 6m, and 8m, and the buried depths of the sand layer are 3m, 5m, 7m and 9m, respectively.

Three acceleration peak amplitudes of surface ground motion, 0.08g (level 1, low intensity), 0.16g (level 2, moderate intensity) and 0.32g (level 3, high intensity), are chosen to simulate the different levels and intensities where the earthquakes are encountered.

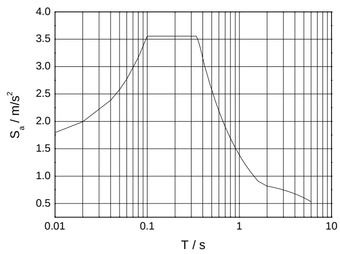
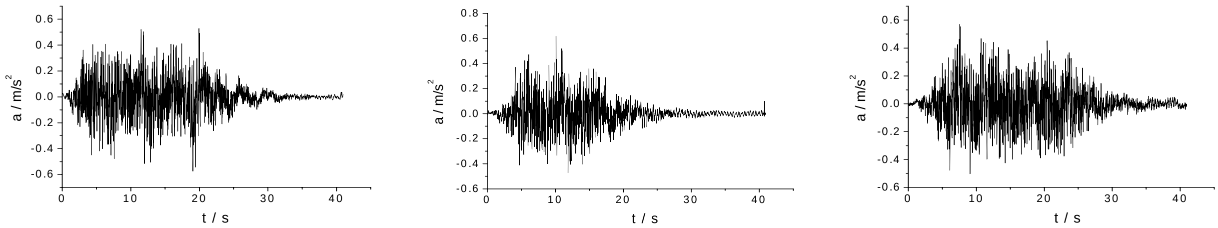
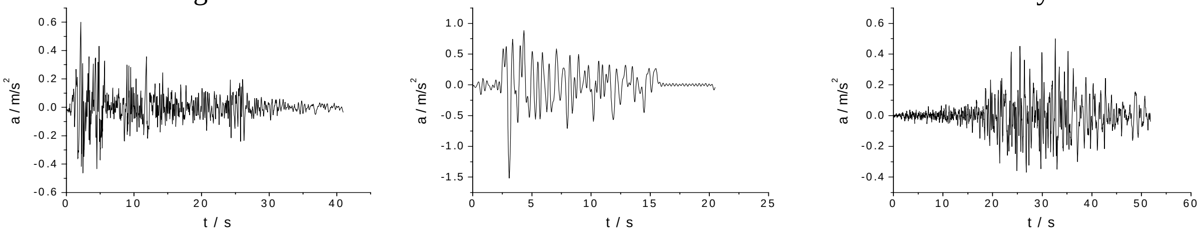


Figure 5 Standard response spectrum



(a) AW1 (b) AW2 (c) AW3

Figure 6 Artificail seismic acceleration waves on the bedrock used in analysis



(a) RW1 (El-Centro wave) (b) RW2 (Qianan wave) (c) RW3 (Tangshan wave)

Figure 7 Actual seismic accelaration histories used in the numerical simulation

3.2 Results of Artificial Seismic Wave Inputs

To study the effect of liquefaction on displacement spectra, the standard response spectrum is converted to standard displacement spectrum according to Eqn. 3.1.

$$S_d = \frac{1}{\omega^2} S_a \tag{3.1}$$

The displacement spectra on liquefaction sites are compared with standard displacement spectrum and the displacement spectra on liquefaction sites are averaged to remove the influence of depth and thickness of sand layers.

The Fig.8 shows the comparison results where the bold line is the standard spectrum and the fine line is the average result of different depth and thickness of sand layer under three artificial seismic accelerations and the liquefaction-increment displacement response spectrum are shown in Fig.9.

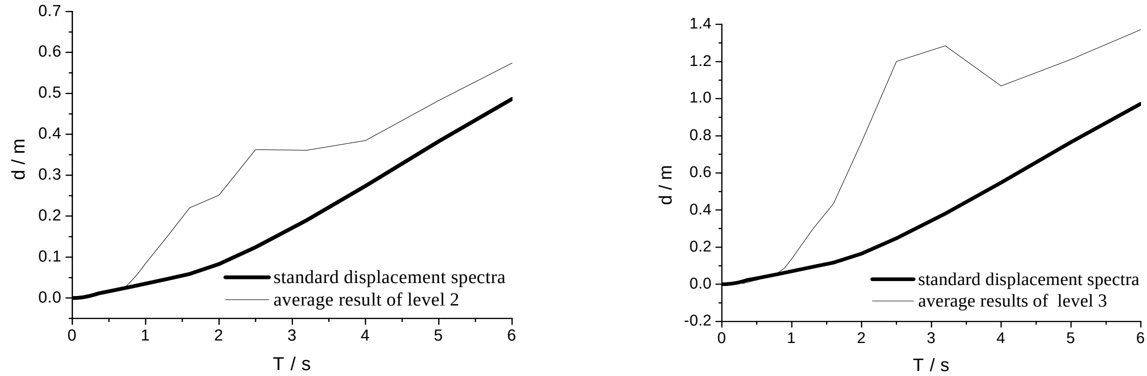


Figure 8 Comparison between standard displacement spectra and displacement spectra of liquefaction sites under artificial seismic accelerations

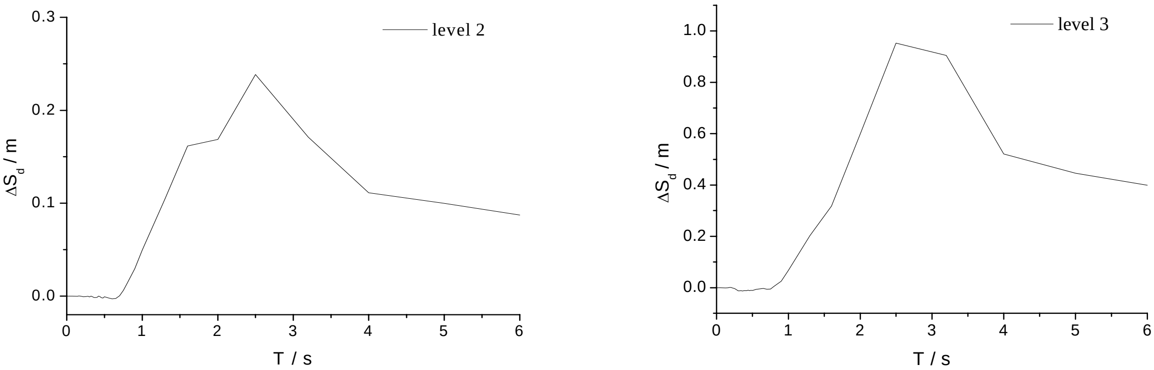
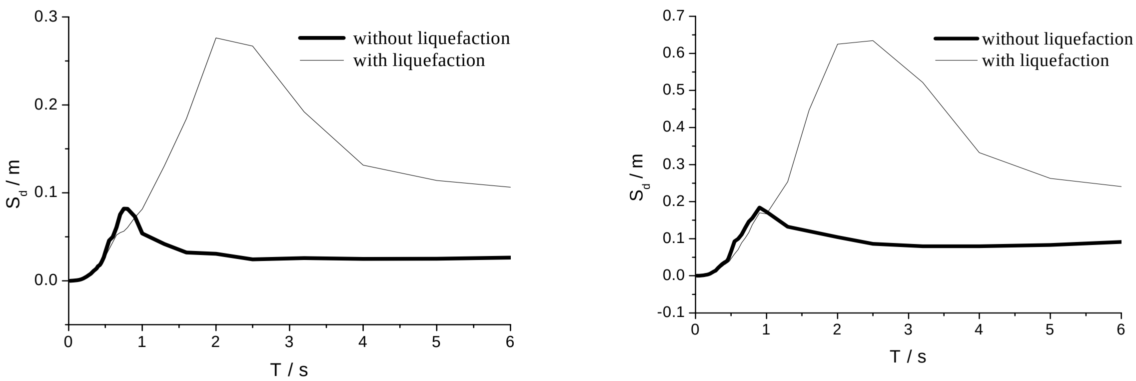


Figure 9 Liquefaction-increment displacement response spectrum under artificial seismic accelerations

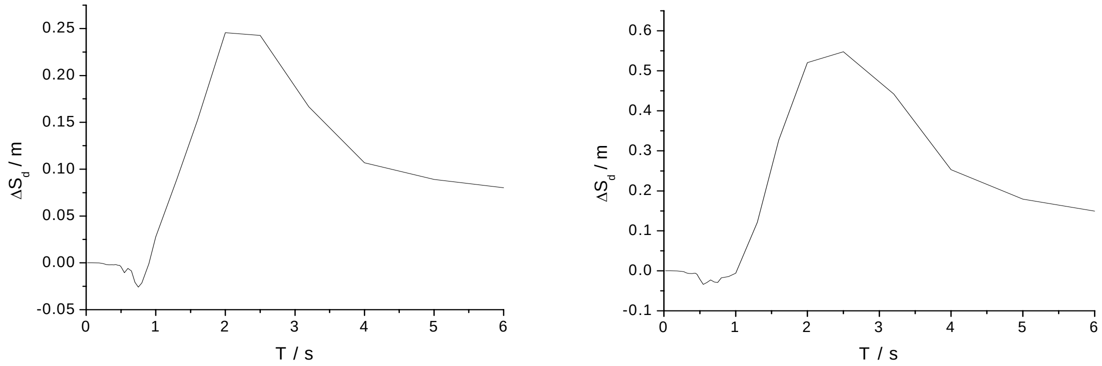
It can be seen from the Fig.8 and Fig.9 that
(1) Liquefaction always magnifies the displacement response spectra.
(2) The effect of magnifying begins to be larger while the period is larger than 1s.
(3) For level 2, the effect of liquefaction on displacement response spectra in the range of 1.5s-4s is the most magnificent about 3 times of standard response spectrum.
(4) For level 3, the effect of liquefaction on displacement response spectra in the range of 2s-5s is the most magnificent about 4 times of standard response spectrum.
(5) Liquefaction make the low frequency part of displacement spectrum increasing and the increment is 0.1-0.3m for level 2 and for level 3 it is 0.5-0.8m.

The results of actual seismic accelerations are shown in Fig.10 and Fig.11. It can be seen from the Figures that
(1) Liquefaction always magnifies the displacement response spectra, which begins to be larger while the period is larger than 1s.
(2) For level 2, the effect of liquefaction on displacement response spectra in the range of 1.5s-4s is the most magnificent and the increment is 0.1-0.25m.
(3) For level 3, the effect of liquefaction on displacement response spectra in the range of 2s-4.5s is the most magnificent and the increment is 0.3-0.55m.



(a) level 2 (b) level 3

Figure 10 Comparison between standard displacement spectra and displacement spectra of liquefaction sites under actual seismic accelerations

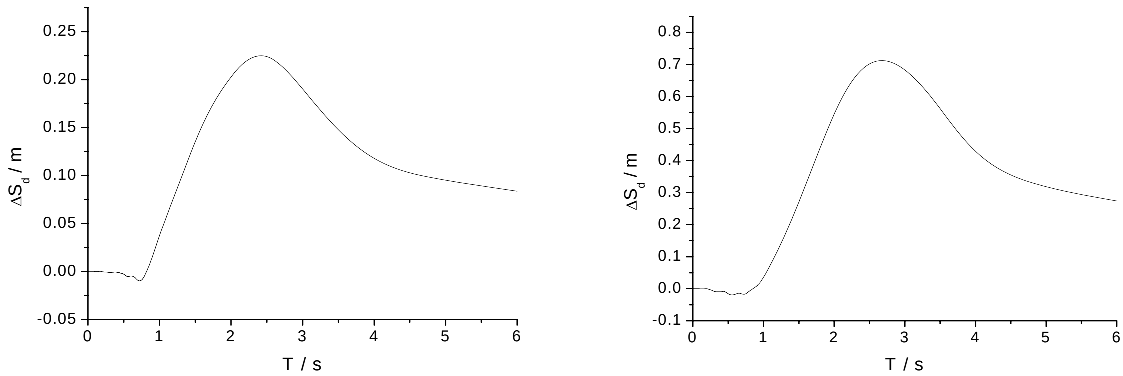


(a) level 2 (b) level 3

Figure 11 Liquefaction-increment displacement response spectrum under actual seismic accelerations

3.3 Comprehensive Results

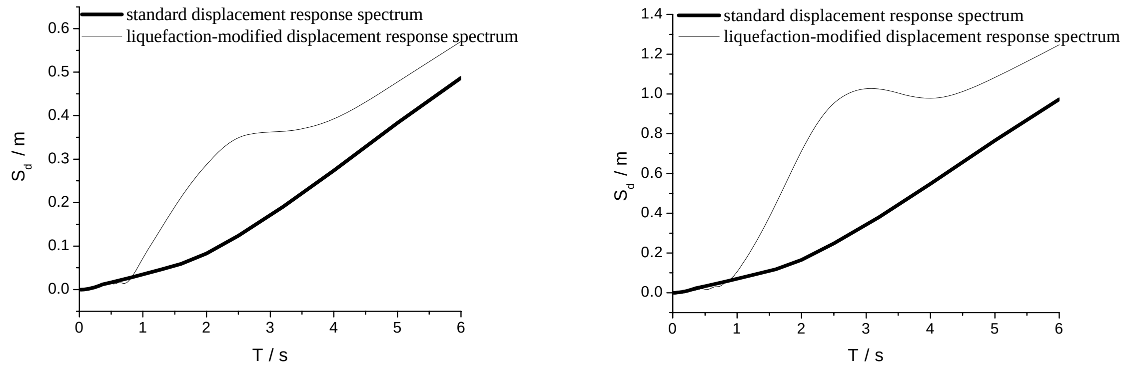
The comprehensive results can be obtained considering the theoretical analysis and actual earthquake records and the liquefaction-increment displacement response spectrum are shown in Fig. 12, in which ΔS_d indicates the increment influence of liquefaction on each period component in displacement response spectrum.



(a) level 2 (b) level 3

Figure 12 Liquefaction-increment displacement response spectrum

Putting the liquefaction-increment displacement response spectrum on the standard spectra, the Liquefaction-modified displacement response spectrum can be obtained shown in Fig. 13. From Fig. 13, it can be seen that the liquefaction always enlarge the displacement response spectrum especially in the range of 1-5s.



(a) level 2 (b) level 3

Figure 13 Liquefaction-modified displacement response spectrum

CONCLUSION

In this paper, the effect of liquefied soil layers on displacement spectra is discussed and the revised displacement spectra due to liquefaction are presented.