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IMPORTANCE OF SOIL AND FOUNDATION DURING EARTHQUAKES

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INTRODUCTION

The effects of an earthquake are mainly viewed with the damages caused to the superstructures of an engineering structure alone. Most of the structural studies and designs advanced thereby deal with earthquake resistant construction of superstructures exclusively. But for the earthquake resistant design to be of any practical purpose the structure must be able to withstand the erratic sequence of the ground motion with a factor of economy also. In this context, every detail, which might be the reason for magnifying the damage must be looked into. Herein, the behaviour of soils under pulsating loading conditions is studied. Attempt is made to bring out the importance of soil and foundation in earthquake resistant design and construction.

BEHAVIOUR OF SOIL DURING EARTHQUAKES

The response of any structure depends mainly upon the interaction of foundation soil system. The forces during the earthquake may be damped or increased depending on the foundation-soil condition. Apart from this, during an earthquake an element of soil in the ground is subjected to a complex system of stresses and deformations resulting from the erratic sequence of the ground motion. However, in many earthquakes the major part of the soil deformation may be attributed to the upward propagation of shear waves from the underlying layers, so that, an element of soil may be considered to be subjected to a series of stress pulses which reverse in direction and change in magnitude. Thus, the earthquake acceleration induces in the soil below the foundation of structures and earth embankments a series of cyclic stress pulses in the order of 30 to 40 pulses. In the case of soil specimen below a horizontal ground surface there may be no shear stress on any horizontal plane. The normal stresses on these planes remain constant while cyclic shear stresses are induced for the duration of ground shaking. Soil specimens in a slope or embankment are acted upon by dead load stresses causing intitial normal and shear stresses to act on any plane. The cyclic shear stresses produced during earthquakes are superimposed over these initial sustained stresses.

BEHAVIOUR OF CLAYS

The strength deformation characteristics of the soil under idealised pulsating loading condition of the form shown in Figure 1, have been investigated, (Seed and Chan 1966). In the case of clays such cyclic stress applications cause deformations to occur during each stress cycle (as shown in Figure 2a), the cumulative effect of which may be excessive deformations or failure. It must be noted that none of these cyclic stress levels cause failure by itself. The resistance exhibited by clayey soils to pulsating loading conditions depend upon primarily the following three factors as illustrated in Figure 2b, Seed and Chan (1966).

1. Magnitude of sustained stress
2. Magnitude of pulsating stress
3. Number of stress pulses.

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Apart from these the form of relationship also depends upon the nature of loading conditions, the soil type, frequency, duration and form of stress pulses.

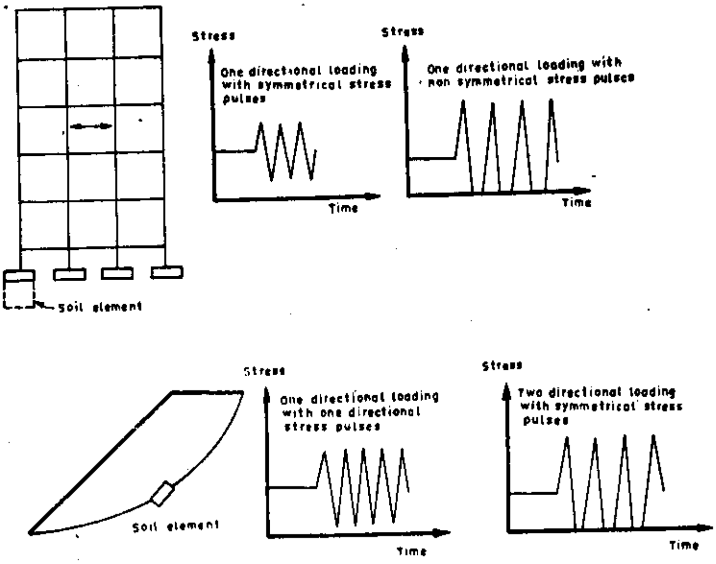


Fig. 1. Stress Condition on Soil Element During Earthquakes.

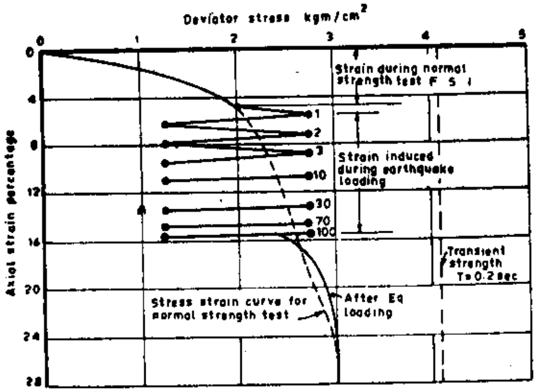


Fig. 2a. Stress Versus Strain Relationship under Simulated Earthquake Loading on Clay.

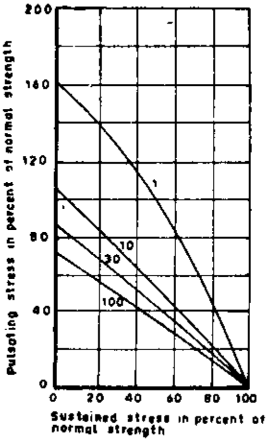


Fig. 2b. Relationship of Sustained and Pulsating Load Intensity for Clay.

During earthquakes the dynamic loading causes cyclic strains, which result in local dynamic soil failure or excessive settlement of foundations. In the case of embankments slope failure of deformations exceeding permissible limits are encountered. Under certain conditions there is also a likelihood of excessive pore pressure to develop in soil layers underlying at least some failure regions. These increased water pressures cause land-slides and slope failures to occur due to creep. Alternatively, when the pore pressures dissipate in the area subjected to sliding large settlements take place. The above mentioned phenomena was described as the reason for damages in the Montana earthquake, 1959 and Alaska earthquake, 1964 (Scott 1965, Seed and Chan 1966). Develop-

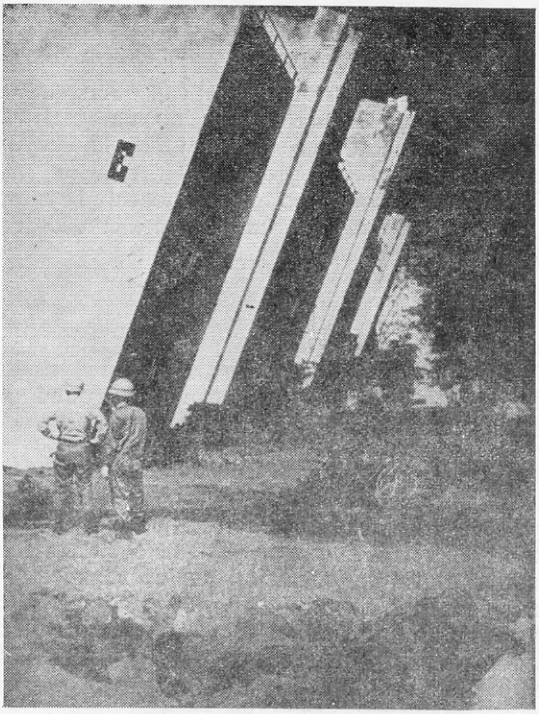


Fig. 3. Foundation Failure during 1964, Niigata Earthquake.

Fig. 4. Cracks in Building Floors due to Liquefaction During 1934, Bihar-Nepal Earthquake.

ment of dynamic triaxial and oscillatory shear apparatus (Seed and Fead 1959, Peacock and Seed (1967), have made it possible to evaluate the soil strength under pulsating loading conditions. Knowing the significant number of stress pulses expected, relationships under dynamic loading conditions of the soil can obtained, (Seed and Chan 1966). Proper safety factors can then be introduced in the normal static stress-strain curves to approximate the behaviour of soil during earthquakes. Thereby, the excessive deformations can be guaranteed against by proper interpretation of dynamic test data. Recently these soil test data are also utilised advantageously in a total stress analysis to compute displacements of embankments and earth dams under earthquake loading conditions (Seed 1966).

BEHAVIOUR OF SANDS

The behaviour of sands subjected to pulsating loading conditions is entirely different from that of clay. When dry sand is vibrated with accelerations of certain intensity it gets compacted resulting in settlement of the ground surface, which in turn, may induce differential movement of engineering structures.

When a saturated sandy ground is subjected to earthquakes, the passage of seismic waves cause pulsating stress applications, resulting in readjustment of the sand particles. These cyclic stress applications cause increase in pore pressures. Though the sand deposit may remain stable till certain number of stress cycles, further increase in number of cycles causes a sudden unstable condition to be reached. Under this state the developed pore pressures equal the confining pressure resulting in entire loss of strength. Thus, the sand deposit reaches a liquefied state. Much of the field and laboratory tests to investigate the phenomena of liquefaction revealed that liquefaction potential is controlled by the following factors (Prakash and Mathur (1966), Seed and Lee (1966), Lee and Seed (1967) and Peacock and Seed (1967).)

1. Magnitude of cyclic stress or strain
2. Number of stress or strain cycles.
3. Initial relative density.
4. Confining pressure.

During an earthquake the liquefaction of sandy ground causes following general damages :

1. Subsidence or tilting of structures due to decrease in bearing capacity.
2. Horizontal land-slides of wide areas.
3. Deformation failure in earth-retaining structures due to increase in earth pressures and decrease in resistance to horizontal slides.
4. Rise of underground structures by buoyancy.
5. Fissures and cracking in natural slopes and man made embankments.
6. Fissures and cracks in foundation and floors of buildings.

Devastating damages of these types have occurred in the past earthquakes such as New Madrid (1911), Kansu (1920), Bihar-Nepal (1934), Niigata (1964) etc. Some of the typical building failures are illustrated in Figures 3 and 4.

The damages encountered in the Bihar–Nepal earthquake (1934) and Niigata (1964) are of particular significance and are typical examples of damages due to liquefaction of general areas. Figure 5, shows the so-called slump belts during Bihar–Nepal (1934) earthquake. In these belts there was an intensification of the earthquake effects; the tilting and subsidence of the structures were maximum. Similar damage zones of general damage during Niigata (1964) earthquake are shown in Figure 6. (Ohsaki

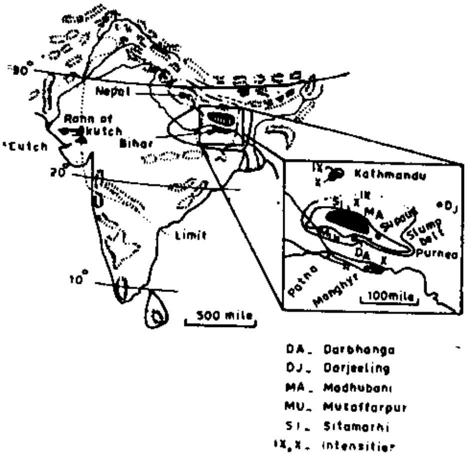


Fig. 4. Slump Belts of Bihar-Nepal Earthquake.

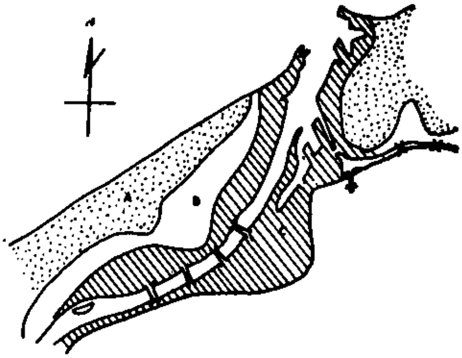


Fig. 6. Different Zones of Damage Niigata Earthquake.

1966). For the different damaged zones the N-values at site are also given in Table 1. This signifies the importance of the insitu density conditions.

Table 1. Different Damage zone in Niigata (1964) earthquake.

Classification	Zone A	Zone B	Zone C
	No Damage	Small Damage	Heavy Damage

The N-value in Intermediate and Heavy damaged zones.

Depth (m)	2 — 5		5 —10		10 —15		15 — 20	
Zone	B	C	B	C	B	C	B	C
No. of Samples	226	302	390	525	358	501	239	432
Mean N-value	5	5	21	8	31	20	36	33

Another important phenomenon associated with liquefaction of sand is the occurrence of landslides aggravated by different processes. The primary reason for heavy damages encountered in earlier mentioned Alaska (1964) earthquake is mainly the landslides. Excellent treatment of landslides due to liquefaction, their process and mechanism is available (Seed 1968).

It is possible with the present day state of art to safeguard against damages resulting from liquefaction by interpreting advantageously the laboratory test data and through theoretical analysis, (Seed and Lee (1966), Seed and Idris (1968), Prakash and Gupta (1968).

IMPORTANCE OF TYPES OF FOUNDATIONS

In many past earthquakes the damages and their reasons have been studied in detail. During many such instances it was noted that no radical conclusion could be arrived at to specify the reasons for different degrees of damages to similar superstructure designs and constructions. Exhaustive studies were made to explore the reasons for damage in the Mexico (1957) earthquake, (Thornley and Albini (1957). The damages were studied with respect to height, material, standard of construction etc. But, no relation could be observed between building heights, structural types and design material of construction regarding the extent of damage. However, definite relation existed between foundation types and extent of damages. The different types of foundation used in Mexico City during the year 1957 are illustrated in Figure 7. Buildings classified according to the type of foundation and various degrees of damages are shown in Table 2. It is evident that structures resting on pile foundations behaved far better than others resting on raft, compensated raft or mat on wooden piles. The importance of rigidity of the connection of foundation with super-structure can also be observed.

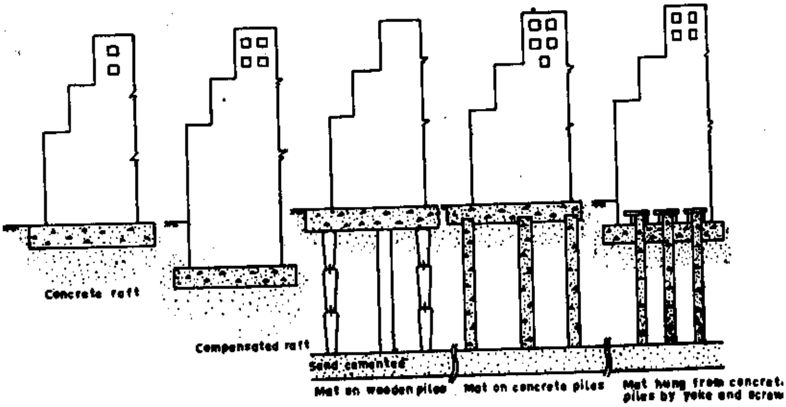


Fig. 7. Types of Foundations in Mexico City.

Table 2. Damage extent and type of Foundation in Mexico Earthquake.

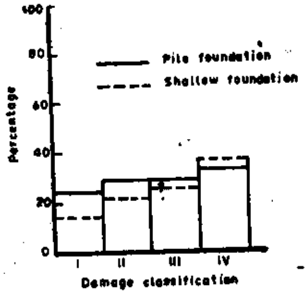
Buildings classified according to foundation	Not damaged	Damaged	Total
1. Concrete mat plain	2	5	7
2. Concrete mat compensated	0	8	8
3. Mat supported by sectional wooden piles	3	12	15
4. Mat supported by long concrete piles	6	0	6
5. Mat having adjustable yokes hung from piles	1	9	10
6. Not Classified	0	1	1
Total	12	35	47

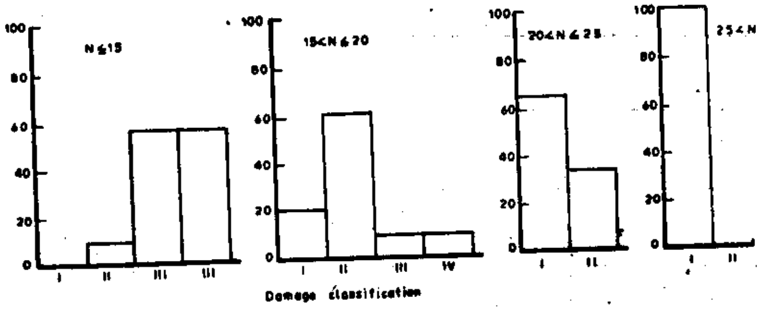
The records of earthquake effects of Niigata (Japan) earthquake of 1964 are the only available data wherein detailed evaluation regarding extent of damage and foundation types was attempted (Kishishida 1966). The damage to reinforced concrete buildings in damage zone C was analysed. It is seen from Table 3 that a large percentage of buildings having spread foundations suffered more damage than those resting on piles, Figure 8a (Kishishida 1966).

Table 3. Damage extent and type of Foundation in Niigata Earthquake.

Type of foundation	Damage Extent No and Slight (I II)	Damage Extent Intermediate and Heavy (III IV)
Shallow foundation	36%	64%
Piled foundation	45%	55%

Among the buildings on shallow foundations those on mat foundations suffered the least damage and buildings on strip footings performed better than those on isolated footings. Also, from the figure 8b it can be observed that the extent of damage depends on the N-value of the soil on which the foundation rests.





Fig, 8a. Damage to Buildings with Reference to Foundations.
Fig. 8b. Percentage Damage to Buildings on Shallow Foundation.

The analysis of pile foundation damages are represented in Figure 8c. The damages to pile foundations depend upon the strength of the soil at the tip of the pile, embedded length of the pile and N-value variation with depth.

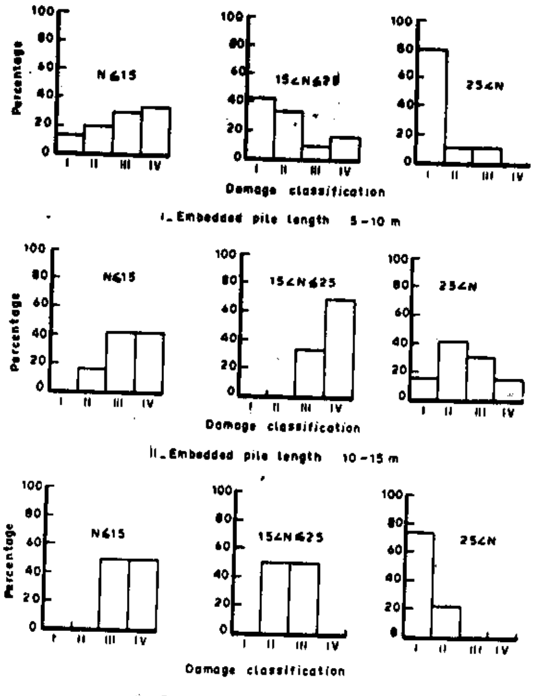


Fig. 8c. Histogram of Damages to Buildings in Pile Foundation.

The importance of these factors were further evident during the examination of the performance of bridges and their foundations during Alaska Earthquake (1964),

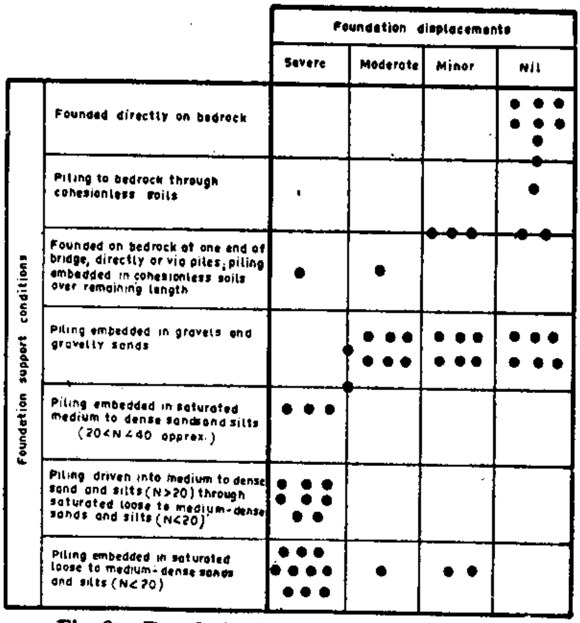


Fig. 9. Foundation Displacement and Support Condition.

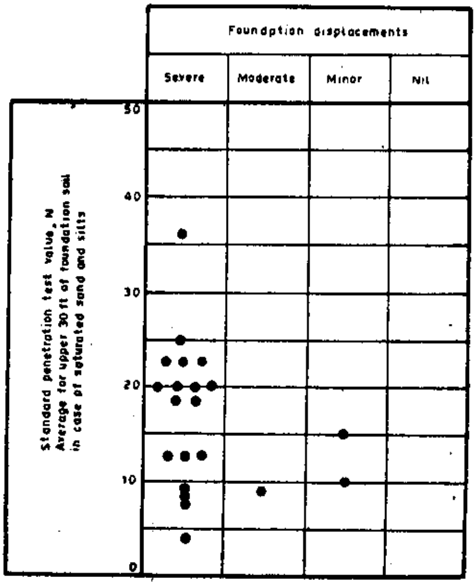


Fig. 10. Soil Strength and Foundation Displacement.

(Seed at al 1969). Attempt was made to ascertain the relationship between the severity of foundation displacements and the density of soil on which they were supported. The performance of foundations and the importance of soil conditions are evidenced in Figures 9 and 10. It was also observed herein that super-structures founded on pile bents and two way battered pile groups suffered worst damage.

GROUND CONDITIONS AND STRUCTURAL RESPONSE

An important refuge to the earthquake resistant designer is the response spectrum technique. By this the combined influence of amplitude of ground acceleration, their frequency component and to some extent the duration of the ground shaking on different structures are represented by means of a plot showing the maximum response induced by the ground motion. Usually the response is considered for single degree freedom oscillators with different periods and damping. It is possible to evaluate response with respect to acceleration, velocity or displacement. The most important function of response spectrum till today (1970) has been to evaluate the maximum lateral force developed in a structure subjected to base motion. Generally in preliminary designs the maximum acceleration and thus the inertia forces are evaluated directly from the acceleration spectrum, with the knowledge the fundamental period of the structure. For multi-degree systems the higher modal effects are superimposed. Of particular importance in the response spectrum is the maximum ordinate and the fundamental period at which its occurs. Thus the establishment of correct form of response spectra is a very decisive factor in the design.

Most of the engineers do recognise the importance of such a factor. But at the same time they fail to consider the importance of soil condition which manifests such techniques.

It has been observed that the ground acceleration recorded at sites of same general area differed to an extent of 100 percent. Figure 11 shows the variation of ground acceleration recorded at two sites of same general area during San Francisco earthquake of 1957 and for a Japan earthquake of March 23, 1963 (Gutenberg (1957), Hisada et al (1965). However, it should also be recognised that the frequency characteristic of the ground motion and thus the form of response spectrum are also profoundly influenced by soil conditions, as shown in Table 4. Herein the periods at

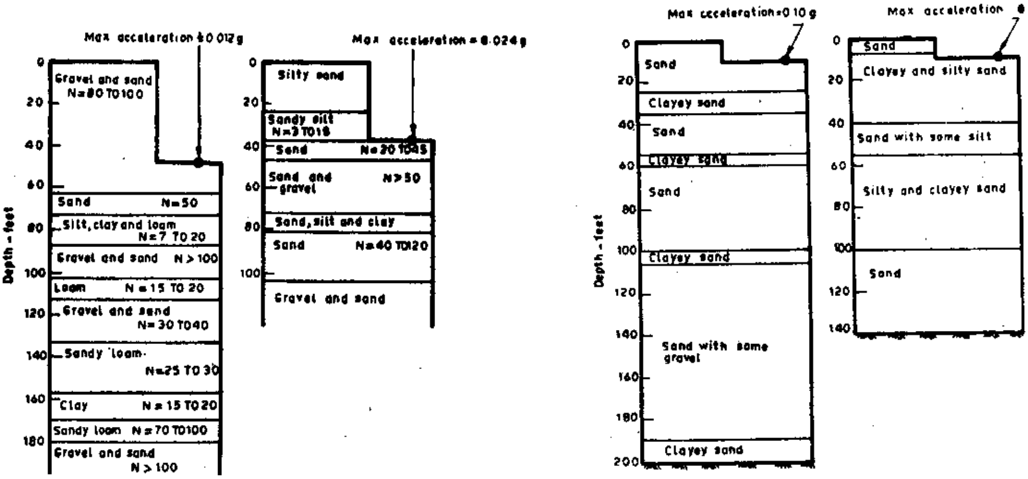


Fig. 11a, b. Effects of Soil Condition on Maximum Ground Surface Acceleration.

Table 4. Influence of Soil Condition on Response.

Sites (arranged in increasing order of softness of soil).	Period at which maximum spectral acceleration is developed in seconds.
A	0·3
B	0·5
C	0·6
D	0·8
E	1·3
F	2·5

which the maximum spectral acceleration developed have been arranged in the order of increasing soil softness for the Japan earthquake of March 23, 1963. (Hisada et al).

It is thus apparent that the frequency component and thus form of spectra are altered depending on the stiffness of soil. So failure to recognise the variation in the form of spectra depending on the variation on soil conditions may lead to false sense of security or insecurity of structures in an earthquake zone.

In recent years analytical procedures have been developed to predict the probable motion at site incorporating the variation in soil conditions (Seed and Idriss (1969).

CONCLUSIONS

Detailed evaluation of the past earthquake effects and the generally adopted earthquake resistant design philosophy reveal that, advanced analytical techniques are utilised to take care of the superstructure exclusively. But the influence of ground conditions and foundations types are generally ignored while evaluating the response or stability of super structures, whereas the extent of damages are largely influenced by soil conditions and foundation types.

When the soil is an area in clayey, dynamic soil failure due to excessive pore pressure development can be expected.

In the general area of loose saturated sand deposits liquefaction of sands may be encountered during earthquakes. The general effects of soil failure would be excessive settlement of structures founded on them and landslide occurrences.

Analytical and experimental techniques are available to safeguard against many of the soil failure conditions.

The performance of structures during earthquake in a general area depends also upon the type of foundation that is adopted. While utilising response spectrum techniques for designs, the influence of ground condition should be realised.

It is believed that if due consideration is paid to the following points the extent of damages to structures in the event of an earthquake occurrence may be largely reduced.

1. If the soil involved at a site is clayey detailed soil tests under different pulsating and sustained loading conditions must be carried out to evaluate the settlement that can be encountered for any condition. It is recommended that the soil samples be consolidated anisotropically and creep movements also be measured.

2. For loose saturated sandy deposits the liquefaction potential must be fully explored.

3. In sandy areas where important construction are to be housed compaction of sands through blasting or vibro floatation need be made.

4. In earth retaining structures adequate counter forts should be provided : they should be properly positioned with respect to sheet pile wall. The section of the wall should be designed with adequate factor of safety to account for increase in earth pressure during earthquakes.

5. In areas where liquefaction can be expected relief wells should be provided. The water table need also be lowered.

6. Generally pile foundations need be resorted to in important structures. The N-value at the tip of the pile should be more than the critical N-value. The foundation and super structure should be properly secured.

7. Shallow foundations when used must rest on stabilised soil at the level of the foundations. Compensated foundations are not to be used during earthquake.

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