SHAKE TABLE TESTS TO INVESTIGATE THE ISOLATION EFFECT OF GEOMEMBRANE IN SOIL

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ABSTRACT

Base isolation and other structural control systems are being developed to minimize the earthquake damage by reducing seismic structural response. Over the years, several types of base isolators have emerged and been installed worldwide in structures to dissipate the seismic energy transmitted to the structure. Generally a base isolator shifts the natural period of the building away from that of the predominant period of the most probable earthquakes and provides additional damping to absorb the energy. The present study focuses on the efficacy of soil and a layer of smooth geosynthetic membrane placed in soil in reducing the seismic response of a structure. Shake table tests are carried out in a 3mx3m tri-axial shaker system with six degrees of freedom. A steel tank fixed to the shake table is used as a container for soil and soil reinforced with smooth geosynthetic membrane. 1/3rd scaled model of a single storey, single bay reinforced concrete space frame with isolated footing has been cast. This model is placed over sand and sand with geomembrane in the steel tank. Sand in dry and saturated conditions are used. Response of the structure is recorded with accelerometers placed at the roof level.

Sine sweep tests are carried out on the structure with fixed base and the structure resting on different soil conditions to assess the effect of soil and soil isolation on the dynamic characteristics of the structure. For this, sinusoidal motion in the range of frequency of 1 to 50 Hz is applied in all three directions with a sweep rate of 1 octave per minute. The structure with different base conditions is subjected to motion corresponding to the response spectrum of Zone III as per the recommendations of Indian standard IS 1893(Part1):2002 to identify the effect of soil isolation on the seismic response. Analysis of results shows considerable reduction in the natural frequency and a reduction in maximum acceleration at the roof level by 40% due to soil isolation with geomembrane. It is concluded that smooth geomembrane and sand acts together as an isolator system in reducing the seismic response of the structure. A concept of using a smooth geosynthetic liner underneath building foundations to dissipate earthquake energy through sliding along the geosynthetic interface can be adopted as an alternative low cost seismic base isolation technique.

INTRODUCTION

Base isolation provides a very effective means of mitigating seismic and vibrational responses in the equipment and systems in nuclear power plants. The reduction in the natural frequency of structures may cause the structural period to be shifted to the right of the falling curve of response spectra given in IS 1893:2000, resulting in a reduced seismic structural response compared to a fixed base structure.

A smooth synthetic liner placed within a soil deposit can dissipate earthquake energy through deformations along the liner interface, thus reducing the intensity of the propagating shear waves. Such a system is referred to as soil isolation because the soil layer above the liner is isolated from the underlying soil deposit that is experiencing the seismic shaking. Soil isolation can be potentially beneficial if applied in the construction of new buildings, slopes, embankments, and reclaimed land using hydraulic fill [1] that is known to liquefy during seismic shaking [2], [3],[4]. For soil isolation to function properly, an allowance has to be made for the deformations to occur along the liner. In addition, the permanent deformations associated with the movement along the isolation liner need to be within acceptable limits if soil isolation is used to protect an overlying building or other structures[5]. The concept of foundation isolation is similar to base isolation except that, in this case, the entire building is isolated from the ground through the use of a geosynthetic liner. Under strong ground shaking the smooth geosynthetic liner underneath the building foundation dissipates earthquake energy thus transmitting reduced accelerations to the overlying structure [6].

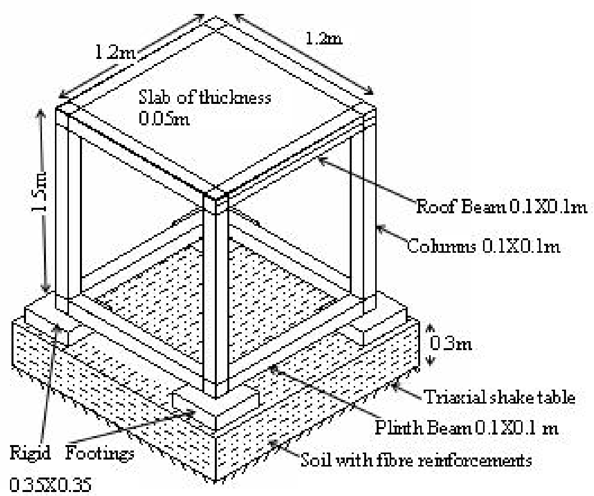
The objective of the present research is to evaluate the efficiency of homogeneous soil and soil reinforced with geomembrane in reducing the seismic wave transmission to the building. It is aimed to estimate the response behaviour of reinforced concrete structures with isolated foundation, resting on a shallow soil stratum of homogeneous or reinforced soil and to study the efficiency of the slip deformations along the geosynthetic interface in reducing the transmission of the base motion to the superstructure.

EXPERIMENTAL SET UP

A 1/3rd scaled model of a single storey, single bay RC space frame with isolated footing was cast. Sufficient mass was added to the structure to maintain the fundamental frequency in the range of 3 Hz to 10 Hz, which corresponds to structures with maximum spectral acceleration according to the response spectra for rock and soil site for 5% damping as given in IS 1893(Part I): 2002[7].

Structure

The size of model is 1.2m X 1.2m c/c between columns.The height of the model up to the top of slab from the top of footing is 1.5m. The slab thickness is 50 mm with reinforcement of 6 MS @ 100 mm c/c both ways at both top and bottom. Plinth beams and columns are 100mm X 100mm with 4-8Tor and stirrups of 3 MS @ 75mm c/c. Roof Beams are 100mm X 100mm with 4-8Tor, stirrups of 3 MS @ 75mm c/c. The isolated footing is 350mm X 350mm X 100mm with 6 MS @ 100mm c/c both ways at both top and bottom. Concrete of Grade M25 was used. A schematic model of the structure is shown in Fig.1.



(a)

(b)

Fig.1: (a) Geometric details of the model (b) Model of the structure

Base isolation

The supporting soil or reinforced soil was filled to a depth of 300mm in a rigid steel tank of size 2mx2m. The supporting soil used for base isolation was well graded dry and saturated dense sand. Polyethlene geomembrane with very low friction coefficient was used. Dense sand was reinforced with this geomembrane which is embedded horizontally in the soil at one third height from the top of soil layer.

EXPERIMENTAL PROCEDURE

The tri-axial shaker system of Earthquake Engineering and Vibration Research Centre (EVRC) at Central Power Research Institute (CPRI), Bangalore, India, was used to carry out the tests on the models. The Tri-axial shaker system consists of 4 vertical and 4 horizontal linear servo hydraulic actuators to provide the motion inputs to the shake table. The t able dimension is 3 m × 3 m with six degrees of freedom, 3 translational and 3 rotational, and a maximum payload of 100 kN. Experimental setup on the triaxial shaker system is shown in figure 2.

Fig.2 : Experimental setup on the triaxial shaker system

A three dimensional single storey building model with isolated footing was placed on the shaking table and its response to harmonic and simulated earthquake motion was measured. Sine sweep test were carried out to find the natural frequency of the fixed structure as well as the structure resting on different soils. Seismic excitations corresponding to seismic zone-III as given in IS: 1893(Part I): 2002 was given to structural model with various base conditions and the response was measured. Comparative studies were carried out by testing the building model placed on different types of soil bed and with fixed base.

To study the response of the fixed base structure, the isolated footings of the model were anchored to the shake table. Accelerometers were placed at the roof level to get the response to the excitations. They were placed at the beam column junction and at the mid span of the roof beam in X and Y directions. Locations of accelerometers are listed in Table 1.

Table 1: Location details of accelerometers

Location of Accelerometers	Direction	Accelerometer Nos.	Location Details
Roof Level	X	A1	At the mid span of roof beam
		A2	At the beam column junction
	Y	A3	At the mid span of roof beam
		A4	At the beam column junction

The structural response to harmonic and earthquake motions was measured. To study the effect of soil, the rigid steel tank was fixed to tri-axial shaker system and a layer of soil or reinforced soil of 300mm thickness was filled inside the tank. Subsequently the building model was placed over the soil bed and the response to shaking was recorded. To study the isolation effect of geomembrane, polyethlene geomembrane with very low friction coefficient was embedded horizontally in the soil at 200mm from the bottom of soil layer and the structural response was measured.

INPUT MOTION

Sine Sweep Test

In this test, a sinusoidal input with continuously varying frequency was applied to the structure for determining the natural frequency of the models. A sinusoidal motion with amplitude of 0.lg was applied in all three directions i.e. X, Y, Z for the structure with fixed base without causing any damage to the rigid structural model.

The response of the structure supported on soil was very less for this amplitude sinusoidal motion. Since the amplitude of motion does not alter the natural frequency of a system, a higher amplitude of 0.2g, which gives a recordable response in the structure was applied to the structure resting on soil. The range of frequency was 1 to 50 Hz. The sweep rate applied was 1 octave per minute. The fundamental natural frequency of the fixed base and compliant base structures was obtained from the frequency response function of the structural response.

Design Response Spectrum for Zone III

Design response spectrum refers to an average smoothened plot of maximum acceleration as a function of frequency or time period of vibration for a specified damping ratio for earthquake excitations at the base of a single degree of freedom system. The design response spectra corresponding to seismic zone-III as given in IS: 1893(Part I): 2002 are shown in Figure 3. In this figure, X and Y denote the two horizontal directions (N-S and E-W) and Z denotes the vertical direction. These spectra were used for the testing of models as explained.

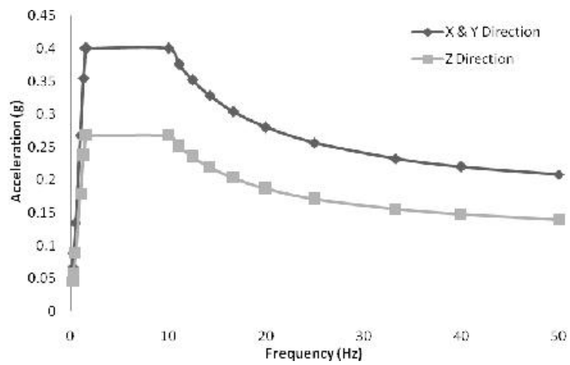


Fig.3: Design response spectra for seismic zone III

RESULTS AND DISCUSSIONS

A study of single bay single storey structural model with isolated footing, resting on various soil conditions, dry sand, dry sand reinforced with geomembrane, saturated sand and saturated sand reinforced with geomembrane is considered. The variation in natural frequencies from experimental results is presented. The variation of maximum acceleration at the roof level is studied for all accelerometer locations for various base conditions. Response spectrum analysis and time history analysis are carried out using spectrum compatible time history for zone III.

Variation in natural frequency

The variation in natural frequency has been studied on structure with the different cases mentioned above. The variation in the natural frequency of the structure from experimental results is tabulated in the Table 2. It is observed that the natural frequency decreases with the increase in flexibility of supporting soil.

Table 2: Variation in fundamental frequency of structural model

Base conditions	Natural frequency(Hz)		
	X	Y	Z
Fixed Base	4.218	4.125	23.25
Dry Sand	3.75	3.5	16
Dry Sand + Geomembrane	3	3	13
Wet Sand	2.5	2.5	12.5
Wet Sand + Geomembrane	2	2	12

Analysis of Table 2 shows that the natural frequency of the fixed base structure is reduced by incorporating a finite mass of soil or reinforced soil below the structure. The effect is more prominent for sand reinforced with the geomembrane layer. The reduction in natural frequency is 28.9 % due to the base with geomembrane reinforced dry sand and 52.6% due to the base with geomembrane reinforced saturated sand. It is also observed that the effect of wet sand itself is nearly 40% and this may be due to the fact that the pore pressure in sand increases due to the excitation and results in a more flexible base. The presence of geomembrane in sand increases the flexibility of the structure thus reducing the natural frequency.

Variation in structural response for Zone III design spectrum

Representative time history of responses at the mid span of the roof beam in X direction for supports with dry sand and dry sand reinforced with geomembranes are shown in figures 4 to 5. The accelerometer recordings represent the responses at the beam column junction and at the mid span of the roof beam in X and Y directions. Table 3 represents the variation in maximum acceleration for excitation corresponding to Zone III. Frequency response spectrum curves for the responses recorded in the accelerometers at the roof level for the structural model subjected to the time history of acceleration corresponding to Zone III are shown in figures 7 to 12. Comparison of structural responses for different base conditions of the structure with dry and wet sand with reinforcement is presented.

Comparison of time history responses at the mid span of the roof beam in X direction presented in figures 4 to 5 and Table 3 shows a reduction in the maximum acceleration values from 7.41 m/sec^2 for a fixed base to 5.45 m/sec^2 for base with dry sand, 4.66 m/sec^2 for base with dry sand & geomembrane. The maximum acceleration at the roof level is reduced by 46% due to the supporting base reinforced with geomembrane. Table 3 shows similar reduction in the structural response recorded by other accelerometers.

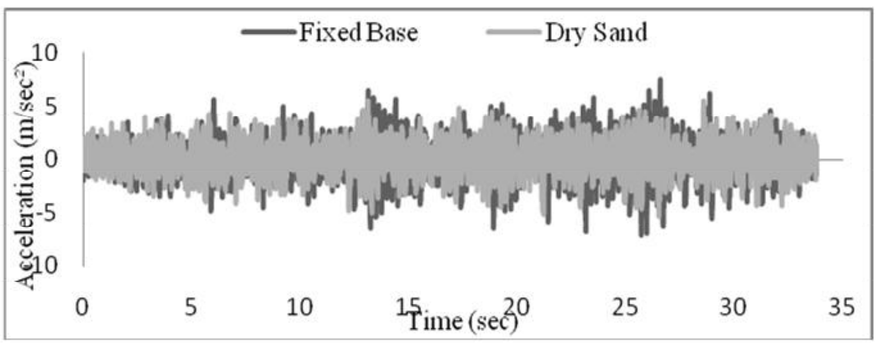


Fig.4 : Time history of response at the mid span of roof beam in X direction for base with dry sand

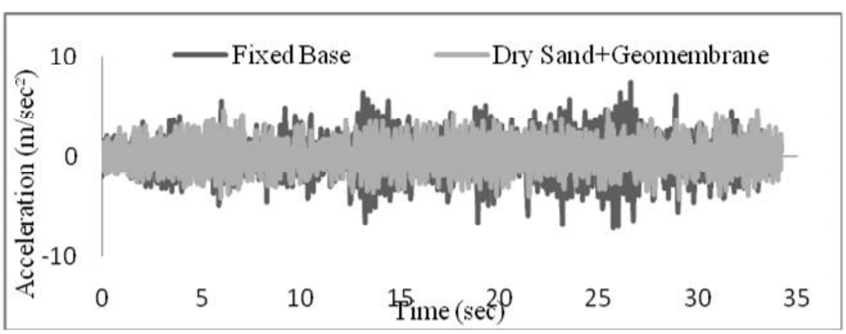


Fig.5 : Time history of response at the mid span of roof beam in X direction for base with dry sand & geomembrane

Table 3 : Variation in maximum acceleration for Zone III

Base Condition	Maximum Acceleration in Accelerometers (m/sec$^{2)}$			
	A2 (X-dir)	A1 (X-dir)	A4 (Y-dir)	A3 (Y-dir)
Fixed Base	9.14	7.41	11.75	7.29
Dry Sand	5.95	5.45	5.28	5.04
Dry Sand +Geomembrane	5.5	4.66	5.82	5.71
Wet Sand	5.33	6	5	5.67
Wet Sand + Geomembrane	5.17	6	5.17	5.83

Frequency response spectrum curves in Figures 6 to 11 show that there is a lateral shift in the fundamental natural frequency of the structure by incorporating the flexibility in the base. It is also seen clearly that the amplitude is considerably reduced for all frequencies upto 50Hz representing an isolation effect. The reduction is maximum for the base reinforced with geomembrane.

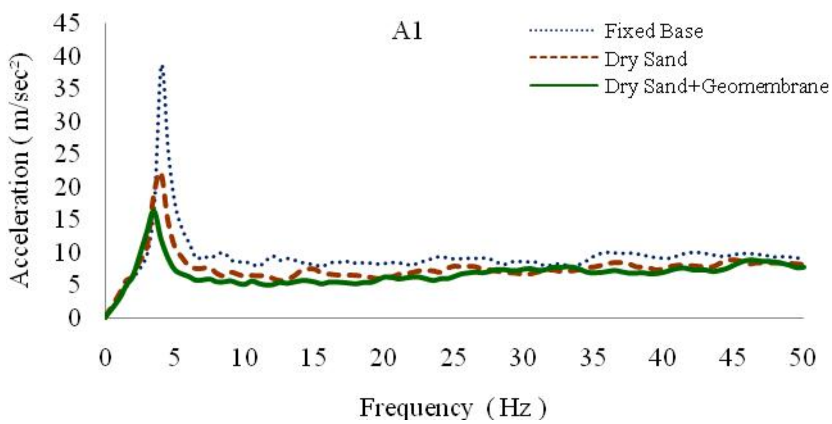


Fig.6 : Frequency response spectrum of response at the mid span of roof beam in X direction for base with dry sand

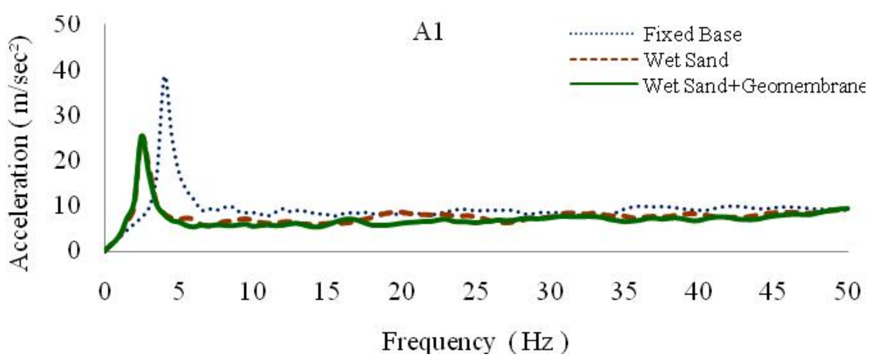


Fig.7 : Frequency Response Spectrum of response at the mid span of roof beam in X direction for base with wet sand

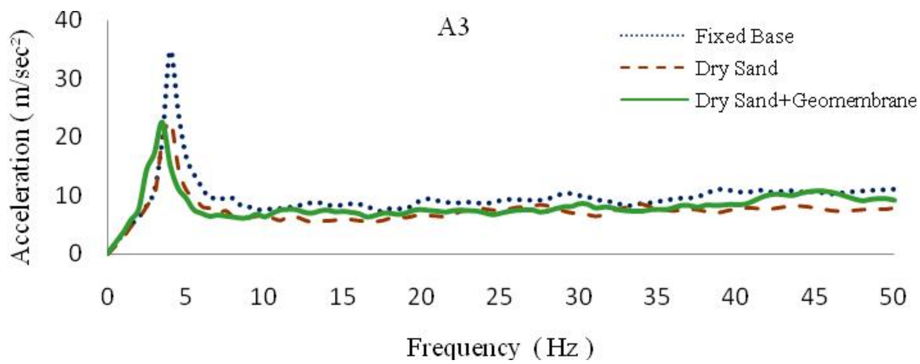


Fig.8 : Frequency Response Spectrum of response at the mid span of roof beam in Y direction for base with dry sand

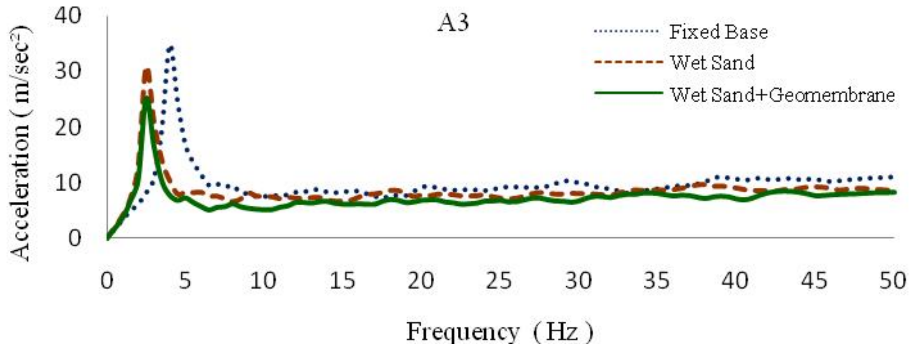


Fig.9 : Frequency Response Spectrum of response at the mid span of roof beam in Y direction for base with wet sand

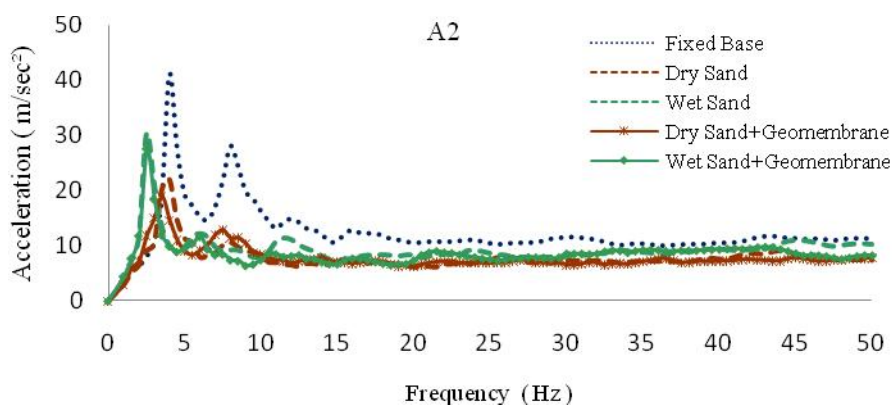


Fig.10 : Frequency response spectrum of response at the beam column junction in X direction for different base conditions

In general it is seen that the base with dry or wet sand reinforced with geomembrane reduces the natural frequency of the structure and the response in the structure to the maximum. This may be due to the slip deformations generated along the geosynthetic interface which reduces the transmission of the base motion to the superstructure.

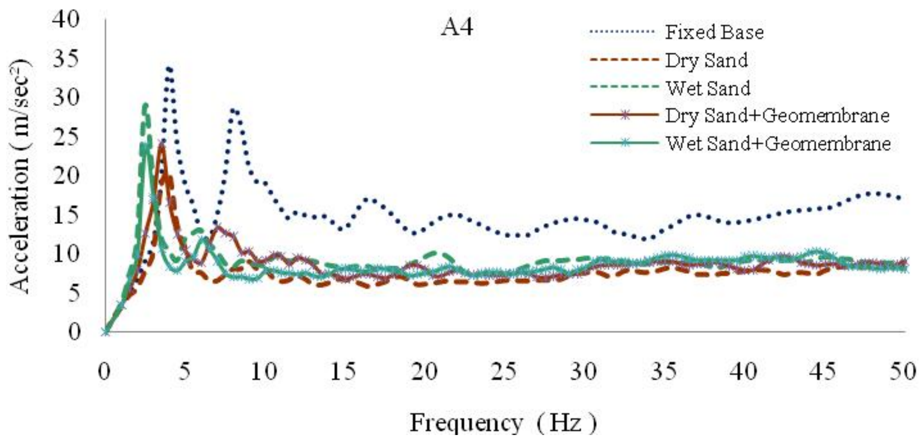


Fig.11 : Frequency response spectrum of response at the beam column junction in Y direction for different base conditions

CONCLUSION

The following conclusions are drawn from the study,

1. The natural frequency of a structure is reduced considerably by the addition of a finite mass of soil to the fixed base. The response in the structure is also reduced due to the addition of soil at the base for an input base motion corresponding to design spectrum for Zone III.

2. Sand in saturated condition acts as a very good base isolator.

3. Geomembrane reinforced wet sand as a base isolation medium causes maximum reduction in the response of the structure.

4. The concept of base isolation with soil or reinforced soil for reducing the natural frequency of the structure and reducing the transmitted base motion intensity can be an economical alternative for conventional methods.

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