Liquefaction Control for Pile Foundation Under a Building Using Rubber-Soil Mixture (RSM)

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***Abstract-* Sustainable material are often applied to mitigate earthquake response in geotechnical engineering. In this paper a layer of rubber-sand mixture (RSM) is used to mitigate earthquake induced liquefaction potential of an RC building. For this purpose, a numerical analysis is carried with 1 D beam model using SAP2000. It is established that around 40% reduction in pile head displacement is achieved with 2.5 m deep RSM layer showing a sustainable solution in earthquake hazard mitigation**

Keywords- Liquefaction, pile foundation, shear modulus, lateral spreading, SAP.

1. INTRODUCTION

Reuse of different scrap material is an important issue in modern trends of different engineering branches. When it comes to sustainable use of scrap material, rubber in the form of scrap tyre may be taken into account for this purpose. Rubber having its elastic property is used as damping material in engineering systems to reduce the effect of shaking or vibration. In civil engineering structures which are very much susceptible to earthquake vibration, rubber materials may be used to mitigate the seismic effect. A number of techniques are there, in which rubber-based isolation systems are used for shallow foundations [1, 2, 3]. In deeper layers, soil characteristics are different from the shallow depths. If some saturated soil layers with low permeability is subjected with earthquake vibration, excess pore water pressure generates and soil loses a major part of shear strength resulting liquefaction. This kind of earthquake induced liquefaction of soil is one of the concerning issues in geotechnical engineering due to its devastating effect on structure. As the liquefaction potential is higher in deeper layer of soil because of higher overburden pressure, its effect on pile foundation is more than shallow foundation [4]. Past earthquakes indicates that piles are affected more in liquefied soil due to inadequate shear strength resulting huge buckling [5]. Buckling failure may occur due to axial loads for slender piles in liquefied soil [6], along with the flexural failure.

Many soil improvement techniques are developed so far to reduce the effect of earthquake induced liquefaction. There are many traditional techniques though widely used, creating various problems like demand of higher energy consumption during installation, material cost, environmental issue, problems in dealing with a large area etc. High energy consumption is one of the issues which is not sustainable in present scenario. In this regard, the use of rubber material seems to be very effective, energy efficient and sustainable. The availability of huge stock of scrap tyre reduces material cost and the mechanical installation process of the proposed technique reduces energy consumption. The main property which is responsible for vibration energy dissipation is the damping property of rubber. Rubber mixed with granular soil (RSM) may be treated as foundation material for this purpose. The geotechnical and mechanical properties of soil mixed with rubber in form of tyre chips increases the flexibility and damping characteristics of soil [7, 8, 9] reducing the earthquake energy transmission to super structure.

In this paper, study is made to investigate the effect of RSM layer around the piles to mitigate the effect of earthquake induced liquefaction. For this purpose, numerical analysis through SAP2000 platform is used. A model of Winkler beam foundation is considered to model the pile. A layer of dry sand mixed with graded scrap tyre pieces (RSM) is placed around the pile for a specific depth. The effect of this layer to reduce pile response in liquefied soil is studied through different numerical analysis.

2. EFFECT OF LIQUEFACTION ON PILE FOUNDATION

The prototype model that is taken to evaluate the variation of shear strength characteristics of soil due to earthquake liquefaction is shown in figure 1. A horizontal liquefiable soil layer is adopted with a steel piles embedded into it is considered. One beam-column element with a diameter of 0.3 m and flexural rigidity (EI) 89.2 MN-m^2 [6] is considered as rigid steel pile in the proto-type model. Total model is placed on a base, which can move laterally but restrained against vertical direction. Now, the model is analysed to obtain the pile response when shaking is applied at the base considering pile end is fixed at the bottom. Analysis is carried through Finite element modelling in SAP2000v14 platform.

For the purpose of earthquake resistance analysis, realistic ground motion is required (PGA based on Richter Magnitude), which may not be possible to have that record at a given site. Even if such recordings available, it is difficult to expect similar ground motion that a future earthquake might generate. Hence, synthetic accelerogram is used considering source, site and path effect. Synthetic accelerogram in which the response spectrum is closely compatible with design response spectrum is closely compatible with the design response spectrum (PGA is based on intensity zone). In this study, a synthetic accelerogram corresponding to earthquake ground motion compatible with the 5% damping design spectrum of the Indian standard code for earthquake-resistant design (IS1893 part-II, 2016) for maximum considered earthquake in the most severe seismic zone (ISZ-V, PGA=0.36) as shown in fig. 2 is used for dynamic analysis.

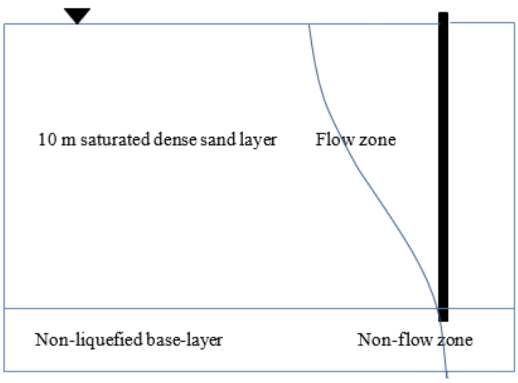

Fig.1. Set up layered profile for analysis of soil

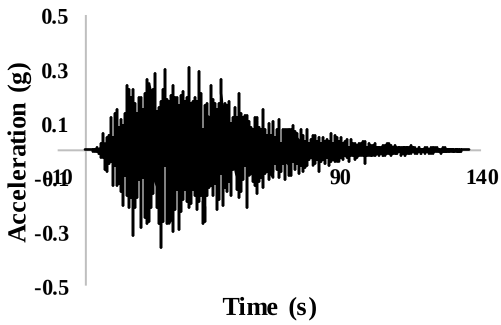

Fig.2. Accelerogram adopted in the analysis (ISZV)

2.1. Numerical analysis with 1-D beam model in SAP2000

Winkler beam model for pile foundation is commonly used to evaluate dynamic pile response in liquefied soil [10, 11, 12]. For this purpose, a Euler-Bernoulli winkler beam with bending stiffness EI=89.2 MN/m^2 is considered to represent the pile. Effect of seismic forces on the soil is evaluated in terms of free field motion. Then, displacement of soil in each node is computed. In this purpose, a soil column with all the soil characteristics shown in table 1 is modelled in SAP2000 platform and the dynamic analysis is carried with the accelerogram shown in fig.2. The deformed shape of the soil column after dynamic analysis is shown in fig. 3 which is taken from SAP2000v14 platform. Displacement of soil node in 1D is also presented in fig. 4. These displacements are applied on the pile statically in an equivalent way to calculate the pile responses. This pile elememt is subjected to the static displacement based on the n^{th} soil vibration mode. In this step, pile response is calculated using SAP2000 considering soil characteristics and soil displacement at different node.

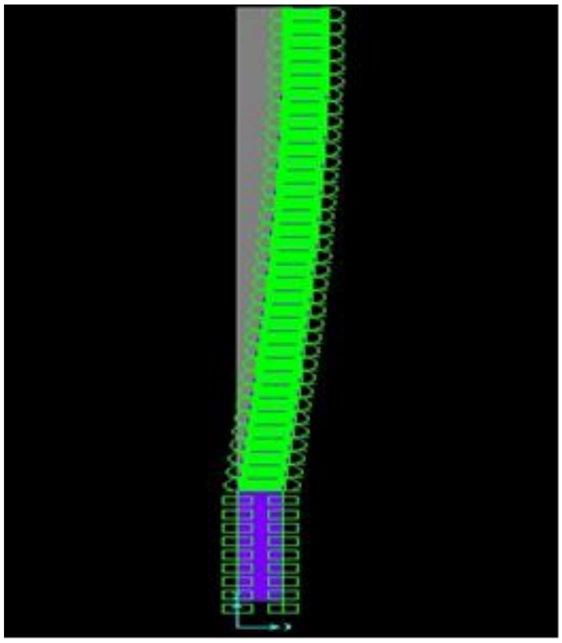

Fig.3. Deformed shape of the soil column from SAP2000v14

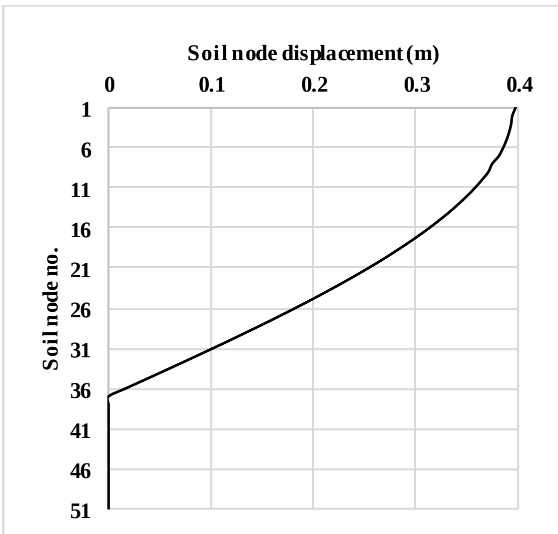

Fig.4(a) Soil node displacement

Then nodal forces is estimated to analyze the effect of dynamic force considring horizontally grounded spring. The stiffness (Kj) provided to the spring is calculated by the equation shown below [13].

$$K_j = 2.4\rho_j V_{s.j}^2 (1 + \mu_j) \qquad (1)$$

Where, ρj = density of the soil at specified soil layer.
Vs.j = shear wave velocity at specified soil layer μj = Poisson's ratio at specified soil layer.

$$F_j = K_j \times U_j(z) \qquad (2)$$

Uj(z) is the displacement of soil computed for seismic analysis at corresponding depth and layer.
In the model, a liquefiable soil layer of 10 m depth with a mass density 19.91 kN/m^3 is taken. The characteristics of the soils are shown in the table 1. The total length of the piles is 10.3 m, of which 10m is inserted into soil layers and 0.3m is above the surface of the soil. A vertical load of 480kN is applied on the pile to encounter the effect of superstructure. Using eq. 1 spring stiffness at each node (j) of the model is calculaled and the spring is again applied with some force according to the following equation (eq.2) to compute the pile displacement and other stress resultants F_j.

Table 1. Soil characteristics

Parameters	Value
Poisson's ratio of dense sand layer	0.35
Shear wave velocity (m/s)	275
Saturated unit weight of dense sand (kN/m^3)	19.91
Initial shear modulus (kPa)	150 x 10^3

2.2. Effect of liquefied soil layer on pile response

Due to liquefaction the shear strength and stiffness of the soil layer is reduced. Due to this buckling on the pile foundation increased and generates additional moment. To model this, the engineering characteristics of the soil is changed to that for liquefied soil layer. The shear modulus of liquefied soil is taken as $1/100^{th}$ of that before liquefaction [14]. The density of soil in liquefied layer is taken as submerged density. All other properties remain same. Finally, the elastically restrained pile model is produced and analysed. For this reason, pile deformation and bending moments will also increase. Figure 3 represents pile responses in liquefied soil and its comparison with non-liquefied soil

From the below figure it may be observed that there is abrupt change in the pile response when soil liquefies due to earthquake vibration. The plots in fig. 5.1 (i) shows the pile head displacement is increased to 0.21 m in liquefied soil from 0.05 m which is in non-liquefied soil. Same observation may be obtained in bending moment also in fig. 5(a) (ii). Maximum bending moment is increased to approximately 230 kN-m in liquefied soil from 15 kN-m bending moment when soil is not liquefied.

3. APPLICATION OF RSM LAYER ON LIQUEFACTION INDUCED PILE RESPONSE

From the previous section of this study, it is clear that pile response is abruptly increased when the soil layer is liquefied. So, to reduce the effect of earthquake on the pile and the soil layer, the use of rubber as isolation seems to be feasible. Rubber in the form of tyre chips mixed with sand around the piles to isolate the seismic effect is analysed by Santoni L, 2001 [9]. The main property which is responsible for energy dissipation is the damping property of rubber. Increase in percentage of rubber in the mixture increase damping properties, but affects the relative density which decreases the stiffness of soil. Due to the reduction of soil stiffness, bending moments and pile deformation is higher at the deeper layer. But easy drainage of excess pore water in higher voids, reduce the effect of liquefaction on flexural deformation in upper layer of soil. The optimum rubber-soil ratio that seems to be effective to fulfil both the purpose is 3:1 [10] in which rubber is 75% by volume. In the proposed model, RSM layer of width 2 m and depth upto 2.5 m is placed around the piles (fig. 4.2). The density of soil and RSM are taken to be 19.8 KN/m3 and 9.5kN/m3, respectively (24). Poisson's Ratio for soil and RSM considered to be same (0.3) while, Young's Modulus are 577.2 MPa and 19.5 MPa, respectively [11].

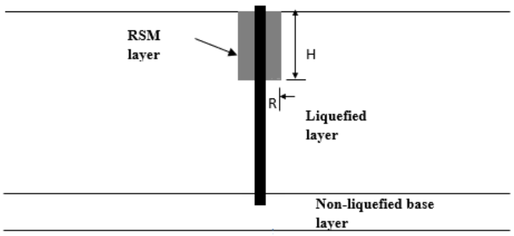

Fig.4(b) Proposed technique to use RSM layer

The same prototype models described in the previous section are used to evaluate the effectiveness of this technique. Only the top 2.5 m portion of the soil model is characterized by the properties of RSM. Rayleigh damping is used to model the damping in the system with modal analysis. Fig. 5(b) presents pile responses due to liquefaction with and without RSM layer. From the figure it is clear that the lateral displacement of pile and bending response are reduced by using RSM. Result shows that pile head displacement is reduced to 0.1225 m and pile head bending moment is reduced to 159.15 kN-m after using RSM around the pile

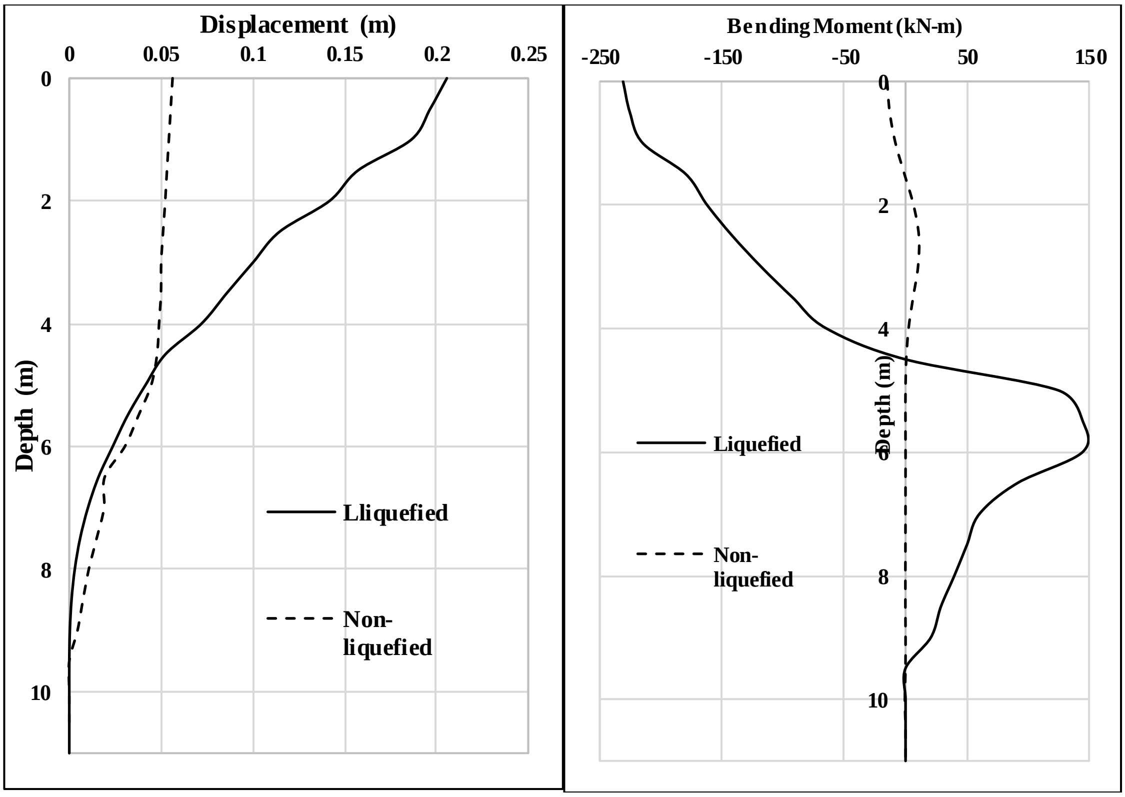

Fig. 5(a) Effect of liquefied soil on (i) pile deformation (ii) bending moment

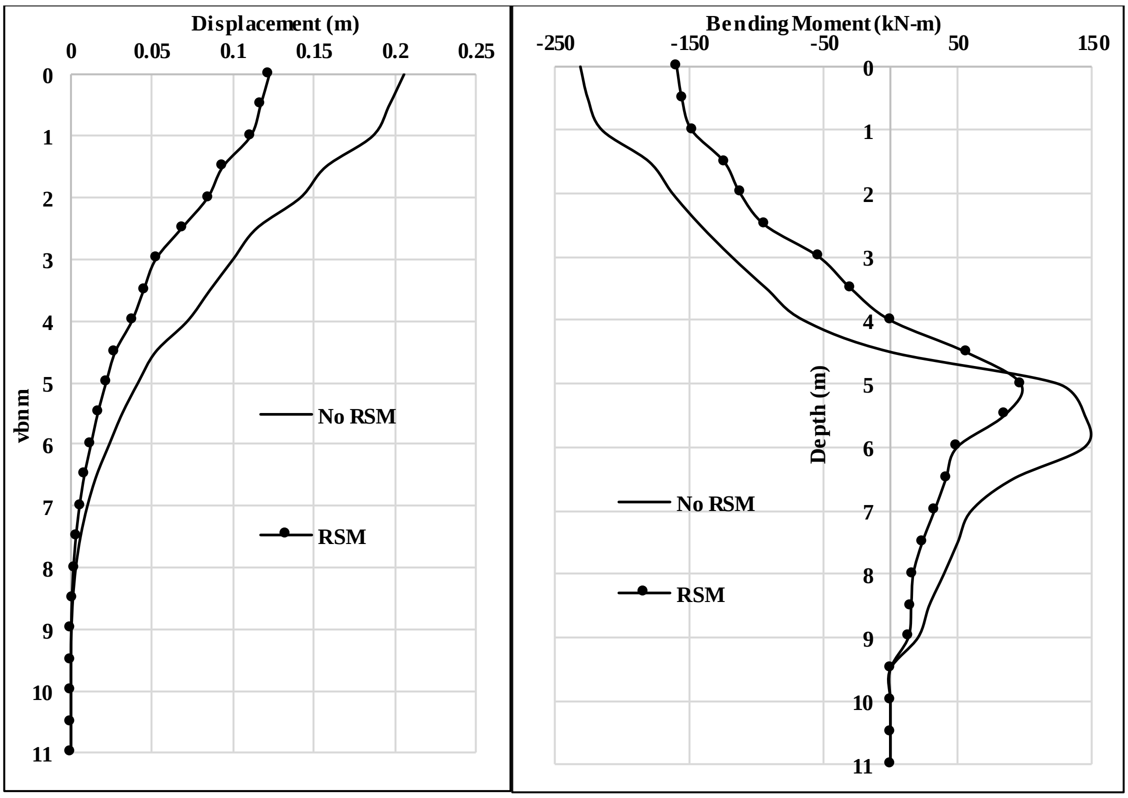

Fig.5(b) Pile responses due to liquefaction with and without RSM (i) Pile deformation (ii) Bending moment distribution

4. CONCLUSIONS

In this study the effect of soil stiffness degradation due to earthquake induced liquefaction on pile performance and its mitigation using RSM is analyzed by numerically. SAP2000 platform is used to compute the soil-pile interaction and the response pattern in simplest way.

1. It is estimated that, due to liquefaction pile response to the earthquake vibration increases abruptly resulting huge damage in pile as well as superstructures. Maximum pile head deformation and BM estimated to be 0.205 m and 230 kN-m respectively after liquefaction.
2. Use of Winkler beam model is the simpliest way to conduct pile response analysis with dynamic load. The soil-pile interaction is carried out by grounded spring and spring stiffness is reduced accordingly to present the soil stiffness reduction during liquefaction.
3. Literature revels the use of RSM as seismic isolation. To study the effect RSM to reduce pile response, RSM layer is applied around the pile upto 2.5 m depth. Results shows that use of RSM layer proves very effective to reduce the pile responses.
4. Final result shows that pile head displacement is reduced to 0.1225 m from 0.205 m and pile head bending moment is reduced to 159.15 kN-m from 230 kN-m after using RSM around the pile.
5. The installation of this technique is very much cost effective and reduces energy consumption as the process is mechanically driven. Only the soil around the pile is replaced by the RSM layer as prescribed. This kind of approach seems to be very much sustainable and enhances the reuse of materials.

5. FUNDING

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