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A numerical study on the dynamic response of scrap tire chips-sand mixture under undrained condition

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ABSTRACT: A wide range of research works have been carried out in soil liquefaction, following the two major earthquakes in 1964, i.e. Niigata and Alaska earthquakes. Numerous researchers have reported the damages suffered by the structures on liquefiable ground. Since then the study of the liquefaction and its countermeasures is of great interest for the researchers. Generation of excess pore water pressure being the key to the initiation of liquefaction, its reduction by any method can serve as a liquefaction mitigation method. This paper investigates the response of scrap tire chips on the generation of the excess pore pressure under undrained condition. Different sand-tire chip mixtures, by weight, were examined to get an optimum ratio having maximum resistance towards the liquefaction. The placement of the proposed material as both horizontal layers and vertical walls were studied separately. The mix with 40% tire chip content was found to be the most effective mix against liquefaction.

1 INTRODUCTION

1.1 *Liquefaction*

Liquefaction is a phenomenon generally seen in the loose saturated granular soils. When these soils are subjected to any kind of loading, may be static or dynamic, they tend to densify. This results in the generation of excess pore pressures in the soil. When these loadings are very quick or sudden, like in case of the earthquakes, the generated pore pressures don't get enough time to get drained, and for a very small time the soil behaves as undrained. In an undrained condition when the excess pore water pressure generates, the effective stress reduces and sometimes even falls to zero. This is a state where the soil loses all its shear strength and starts behaving like a viscous liquid. This is when the soil is said to be liquefied or the soil liquefaction is said to happen. Due to the loss of strength, the liquefied soil can no longer support any structure standing on it. The effect of liquefaction is very fatal in the constructed facilities. Liquefaction has reported to claim many lives and properties in the past.

The liquefaction phenomenon is known long back, but it drew attention after the devastating 1964 Alaska and Niigata earthquakes (Yasuda, 2007). After 1964, many studies had been reported to counteract this liquefaction. The methods like densification, solidification, deep mixing, desaturation, drainage, chemical grouting, etc. are proposed to counteract liquefaction. But most of these methods deal with the improvement of open ground against liquefaction, i.e., before construction of a structure. Use of these methods for the improvement of the soils supporting existing structures is very tough or not possible. Therefore, there is a need of proper countermeasure to improve the soil on which structures are already built. There are very few studies which are reported for the improvement of the soil supporting existing structures.

1.2 *Countermeasures background*

Soil liquefaction results in the lateral flow of the soil in its liquefied state, which contributes to the liquefaction induced settlements. To counteract this, few studies reported the confinement of soil by different methods. Studies by Zheng et al. (1996), Mizutani & Towhata (2001), etc. reported the use of sheet pile wall as confinement method. Later Sáez & Ledezma (2015) proposed the use of secant pile wall. Though these methods reduced the settlement to some limit but still the settlement existed and the studies concluded that just by confining the soil the settlement cannot be reduced. Then researchers carried out different model tests and proposed the methods of confinement along with drainage. Adalier et al. (2004) reported the use of sheet pile walls along with gravel berm to improve the soil below an embankment. Motohashi et al. (2011) and Rasouli et al. (2015) conducted model tests to study the effect of sheet pile walls along with ground water lowering as a liquefaction countermeasure. Later Rasouli et al. (2016) reported the introduction of drains as a liquefaction countermeasure. As liquefaction is mainly reported in saturated soils, studies by Okamura et al. (2003), Ishihara et al. (2003), Okamura & Teraoka (2006), Marasini & Okamura (2015), Zeybek & Madabhushi (2017) etc proposed the air injection method of desaturation as a liquefaction countermeasure.

As liquefaction process mainly results due to the accumulation of the excess pore water pressure, many studies reported different methods to provide fast or quick drainage to the excess pore water pressures that gets generated due to sudden loading. Numerous researchers have conducted tests on the effect of drains on the liquefaction process. Tokimatsu & Yoshimi (1980) and Sasaki & Taniguchi (1982) performed model tests to evaluate the effect of gravel drain to improve the foundation soil and reported the reduction in the uplift of the structure. Later Masakatsu et al. (1992), Orense et al. (2003) and Towhata et al. (2015) carried out shaking table tests to prevent buried pipelines against liquefaction by using drains. The drainage material considered was gravel wall and gravel pile by Masakatsu et al. (1992), recycled concrete crushed stones by Orense et al. (2003) and vertical drain pipe by Towhata et al. (2015).

Any method suggested as a countermeasure should be studied both in undrained and drained condition for better understanding. However, undrained condition is the most ideal condition for the liquefaction to happen. This study proposed the use of scrap tire chips as a replacement material for the foundation soils to counteract liquefaction. This study numerically evaluates the response of sand-tire chips mixtures under undrained condition.

1.3 *Selection of the scrap tire chips as the replacement material*

Any material proposed as replacement material must be cost effective and easily available. To serve the availability and cost effectiveness criteria, the preferable material can be a waste or a by-product.

In the present study, scrap tire chips were considered. In day to day life a huge number of scrap tires are discarded in the landfills daily, hence, the present study can be a small effort to use these wastes in a very effective way. ASTM D6270 (ASTM 2008) specifies three different categories of the scrap tire types used for the application of civil engineering works. They are tire crumbs (length less than 10 mm), tire chips (length in between 10 to 50 mm), and tire shreds (the length is greater than 50 mm). Apart from this, according to Orense et al. (2003), “a material to be used as a drainage material must have sufficiently high permeability for liquefaction remediation and a high resistance against liquefaction”. From the literature, it is noted that the scrap tire chips have very higher permeability than sand. These materials at their compacted state show permeability close to coarse gravels (Grayson et al., 2013). Again, the study by Li et al. (2016) reported that the liquefaction resistance of the soil increases with the increase in the rubber fraction. As these materials can serve as replacement as well as drainage materials, perfectly, it is chosen for the study.

In the present study, a numerical model using finite difference software FLAC3D was developed and the effect of the scrap tire chips, placed as horizontal layers and vertical walls, on the excess pore pressure generation in the soil was studied under undrained condition.

2 MODEL DESCRIPTION

2.1 *Development and validation of the model*

A centrifuge study reported by Karimi and Dashti (2015) was used for the validation of the model. The model consisted of three different soil layers, the top 2m layer was a dense non-liquefiable sand layer, the middle 3m layer of liquefiable sand and the bottom layer consisted of 21m thick dense sand.

The analysis was carried out using a finite difference software FLAC3D version 5.01. Eight noded brick-shaped zones were used for the study. The Finn constitutive model was used to simulate the non-linear behavior of the sands. The Finn constitutive model in FLAC3D actually incorporates Martin et al. (1975) and Byrne (1991) relations into the Mohr coulomb plasticity model. In this study we have used the Finn model along with the Byrne relations. The generation of the excess pore pressures in the model was calculated from the deformation of the soil matrix. The formula proposed by Byrne (1991) in this regard are the following:

$$\frac{\Delta\varepsilon_{vd}}{\gamma} = C_1 \exp\left(-C_2 \frac{\varepsilon_{vd}}{\gamma}\right) \tag{1}$$

$$C_1 = 7600(D_r)^{-2.5} \tag{2}$$

$$C_2 = \frac{0.4}{C_1} \tag{3}$$

Where, ε_{vd} = irreversible volumetric strain; γ = cyclic shear strain amplitude; D_r = Relative density and C_1 & C_2 are constants.

Figure 1 shows the mesh considered for the present study. The upper yellow color represents the dense Monterey sand with relative density of 85%, the middle blue color represents the middle Nevada sand with relative density of 30% and the bottom red portion represents the dense Nevada sand with relative density of 90%. The properties of the three soil layers are presented in the Table 1. The water table was considered at a depth of 1m from the ground surface.

After assigning the model properties, input motion used by Karimi and Dashti (2015) i.e. Large Port Island event presented in Figure 2 was given at the base of the model. The input

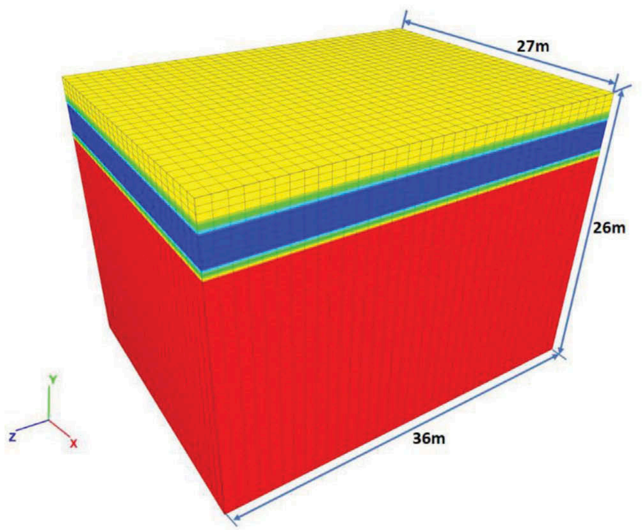

Figure 1. Mesh used in the present study.

Table 1. Properties of the soil used in the model (Karimi and Dashti, 2015)

Properties	Monterey Sand	Nevada Sand 1	Nevada Sand 2
Relative density (%)	85	30	90
Dry density (ton/m^3)	1.65	1.52	1.69
Void Ratio	0.56	0.76	0.58
Friction angle (degrees)	40	31	42
Bulk modulus (MPa)	264.0	92	272.1
Shear Modulus (MPa)	133.3	34.5	101.9

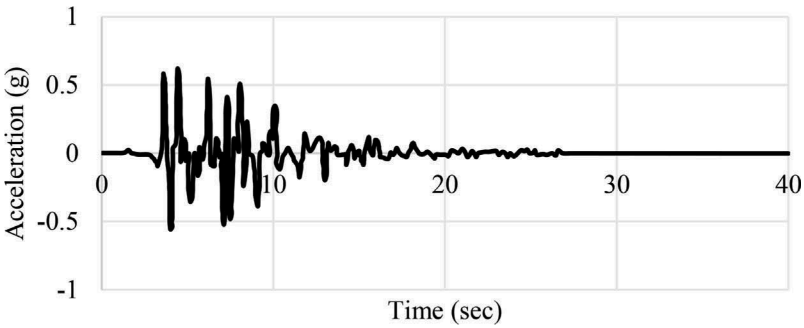

Figure 2. Base Input Motion: Acceleration time history during Large Port Island event (Karimi and Dashi, 2015).

motion has PGA value of 0.58g (Karimi and Dashti, 2015). The pore pressures generated at base of the model, at the bottom of the liquefiable layer, at the middle of the liquefiable layer and at the top of the liquefiable layer were observed. The estimated pore pressures from the numerical modelling were then compared to that of the experimental results and numerical results reported by Karimi and Dashti (2015).

It can be seen from Figure 3 that the pore pressure results of the present study are very similar or close to that reported by Karimi and Dashti (2015), for all the depths considered. However, the excess pore pressure generated at the top of the liquefiable layer is quite different from that of the experimental results. The possible reason for this deviation can be as follows. In all other cases the pore pressure generated at around 10 seconds remains constant up to the end of the shaking, as there is no way for the pore pressures to get dissipated, however at the top of the liquefiable layer the pore pressure seemed to get dissipated after 10 seconds. This might be because of the drainage of the pore water from the top. However, as the analysis was carried out in undrained conditions, the model was unable to capture the exact behavior at the top of the liquefiable layer.

2.2 *Introduction of the scrap tire chips wall in the model*

To investigate the effect of the scrap tire chips as a liquefaction mitigation measure two different orientations of the tire chips layers were proposed in the study. Firstly, the tire chips were placed horizontally at the top of the liquefiable soil layer with the intention to provide faster drainage to the soil and in the second case the tire chips were placed vertically, surrounding a particular soil mass supporting a structure. The same input motion was applied for both the cases and the excess pore water pressure generated were observed.

In case of the horizontal layer, the top 2 meters of sand was replaced with a mixture of scrap tire chips and sand in different proportions. The properties of the mixtures considered in the present study were adopted from the experimental studies reported by Reddy et al. (2015). The properties of the different materials considered are presented in Table 2. In the case of vertical walls, the tire chips were placed as shown in Figure 4 and the analysis was carried out for all the combinations of tire chips and sand mixes.

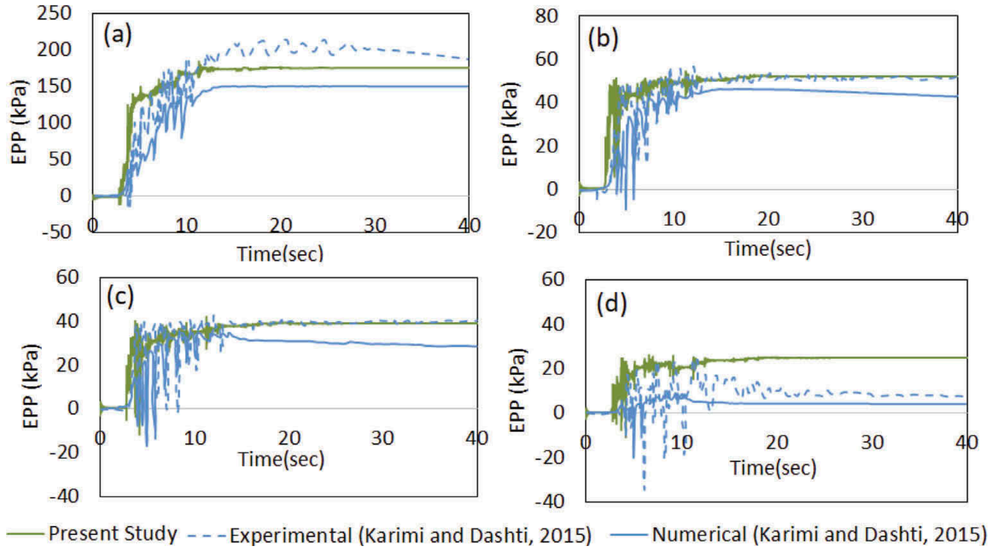

Figure 3. Excess pore water pressures (a) At the base of the model (b) At the bottom of liquefiable layer (c) At the middle of liquefiable layer (d) At the top of the liquefiable layer.

Table 2. Properties of the tire chips and tire chips-sand mixture used in the model (Reddy et al., 2015)

Tire chips: Sand	100:0	70:30	50:50	40:60	30:70	20:80	10:90
Relative density (%)	100	100	100	100	100	100	100
Dry density (ton/m^3)	0.650	0.857	1.082	1.214	1.301	1.396	1.454
Void Ratio	0.66	0.5	0.39	0.35	0.38	0.44	0.55
Friction angle (degrees)	32.8	36.9	41.53	51.34	56.09	52.60	50.85
Shear Modulus (MPa)	5.05	5.35	7.62	9.35	12.3	19.8	25

The excess pore water pressure generated at four different depths i.e. at the top, middle, bottom of the liquefiable layer and at the base were observed. The variation of the excess pore pressures ratio, which is defined as the ratio of the excess pore pressure generated and the effective vertical stress, with time was plotted for different combination of tire chips-sand mixtures. Generally, liquefaction is considered to happen when this pore pressure ratio becomes 1.

3 RESULTS AND DISCUSSION

3.1 *With horizontal tire chips layer*

For all the depths, the variation of the excess pore pressures with time shows a typical behavior, as shown in Figure 3 i.e. the excess pore pressure increased remarkably in the initial 10 seconds and then became constant. Figure 5 shows the variation of the pore pressure ratio with the increasing percentage of the tire chips in the sand.

It can be seen that the pore pressure ratio decreases with the increase in the tire chips content up to 40%, but with further increase in the tire chips percentage in sand, the pore pressure ratio again started increasing. This trend was seen at the top, middle and bottom of the liquefiable layer. At the base of the model, the pore pressure ratio variation is very small i.e. the pore pressure ratio value varied within 0.63 to 0.69 for all the mixes considered in the study.

Initially with small percentage of tire chips the sand was getting liquefied. For 30% and 40% of the tire chips, the loose sand layer didn't liquefy at all, for all the three depths considered

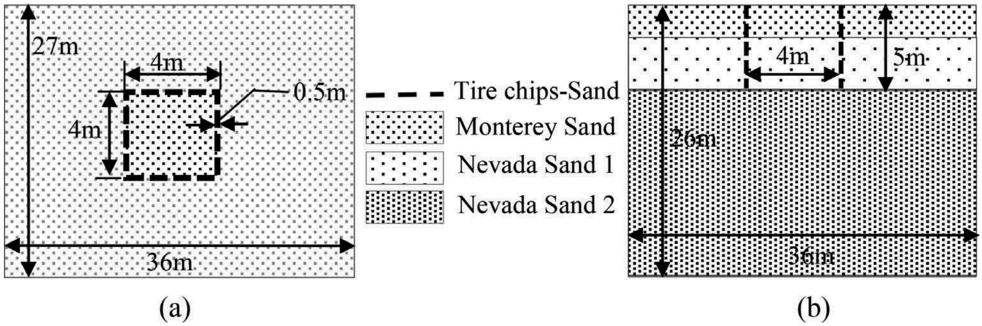

Figure 4. Schematic diagram showing the replacement of the tire chips-sand mixture as vertical wall (a) Plan View (b) Sectional View (Not to Scale)

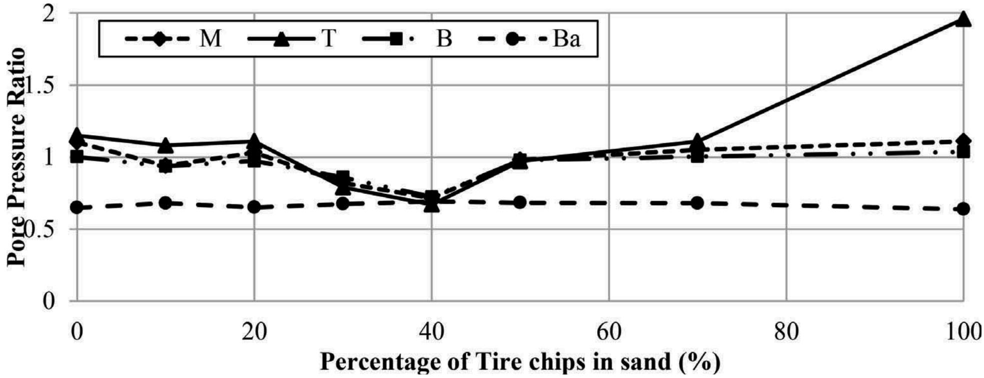

Figure 5. Pore Pressure Ratio due to placement of horizontal layer of tire chips-sand mixture (T- At the top of the liquefiable layer, M- At the middle of liquefiable layer, B- At the bottom of liquefiable layer and Ba- At the base of the model)

and again with further increase in the tire chips the liquefaction occurred. So, the maximum resistance towards liquefaction was seen in the sand having 40% of tire chips. This may be because the void ratio of the mix was the minimum among all the mixes considered. Also as top layer was replaced with a lighter material, the vertical pressure also reduced and hence it might affect the liquefaction resistance of the soil.

At the base of the model there was very less effect of the replacement of the top layer. This might be because of the fact that the total depth of the soil considered was about 26 m and the replacement was done only at the top layer for 2 m.

3.2 *With vertical tire chips wall*

Figure 6 shows the variation of pore pressure ratio with the increase in tire chips content, when the tire chips-sand mix was placed vertically around the soil supporting a structure. For the depths considered, the pore pressure ratio at the middle of the soil mass surrounded by the vertical tire chips walls was not much affected by the placement of the walls.

This vertical wall method may be practically more effective than the results obtained in the study. This is because the numerical analysis was carried out for the undrained conditions during the liquefaction analysis, whereas this vertical chip walls may show more effectiveness when allowed for drainage. So, the presence of the vertical tire chip walls hardly showed any effect in the soil behavior under the undrained condition.

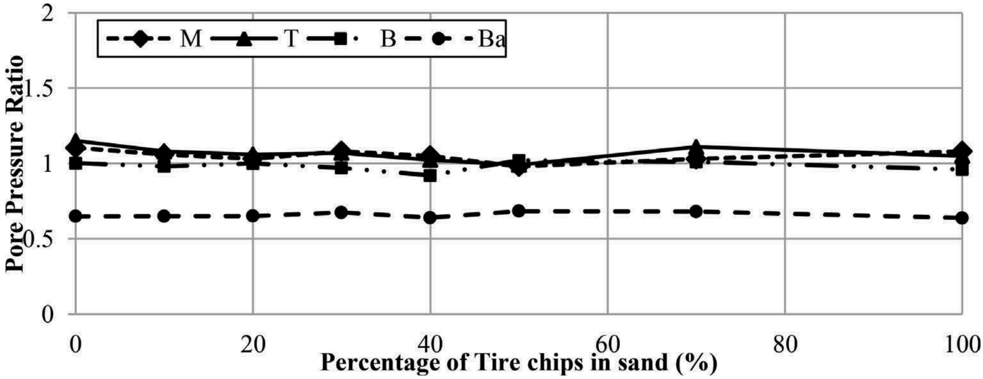

Figure 6. Pore Pressure Ratio due to placement of vertical walls of tire chips-sand mixture (T- At the top of the liquefiable layer, M- At the middle of liquefiable layer, B- At the bottom of liquefiable layer and Ba- At the base of the model)

4 CONCLUSIONS

Numerical analyses were carried out using finite difference software FLAC 3D. The use of tire chips and its mixture with sands at different percentage was proposed as a liquefaction counter-measure in the study. The material was proposed to be used as horizontal layers and as vertical walls. The behavior of the proposed material under undrained condition was considered in the study. The vertical wall mitigation measure didn't give any remarkable difference in the result. So, the conclusions reported are mainly based on the effectiveness of the horizontal tire chips layer under undrained condition.

From the study following conclusions can be drawn:

- The liquefaction resistance of the soil was not much affected with the addition of the tire chips upto 20% by weight, however the effect was remarkable when tire chips were up to 30 to 40%. Further increase in the tire chips percentage reduced the liquefaction resistance of the soil.
- The pore pressure ratio value was found to be minimum for the 40% of the tire chips content in the sand.
- The pore pressure ratio value reduced from 1.15 to 0.67, 1.1 to 0.7 and 1.002 to 0.72 for the top, middle and the bottom of the liquefiable layer, respectively. Not much change was observed at the base of the model.

As the numerical analysis was carried out in the undrained condition the settlement characteristics of soil was not considered during liquefaction and the discussions in this study is limited to the pore pressure generation.

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