Experimental Investigation Into Natural Base Isolation System for Earthquake Protection

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EXPERIMENTAL INVESTIGATION INTO NATURAL BASE ISOLATION SYSTEM FOR EARTHQUAKE PROTECTION

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ABSTRACT

This paper presents the results of experimental investigations into the performance of a well-designed layer of sand, and layer of sand mixed with shredded tire (rubber) as low cost base isolators. The building foundation is modeled by a 200 mm by 200 mm and 40 mm thick rigid plexi-glass block. The model footing is placed in the middle of a 1m by 1m tank filled with sand. The selected base isolator is placed between the footing and the sand foundation. The whole setup is mounted on the shake table and subjected to sinusoidal motion with varying amplitude and frequency. Acceleration values at the shake table, inside the isolation material, and on top of the footing are measured. The displacement of the footing is also measured. The sand is found to be effective only at very high amplitude (> 0.65g) of motion. Among all the different percentage of shredded tire in sand tested, the performance of a layer of 50% shredded rubber tire and sand placed under the footing is found to be most promising as a low cost effective base isolator.

INTRODUCTION

To find an economical and feasible way of designing new structures or strengthening existing ones for protection from the damages during an earthquake is one of the challenges in civil engineering. The conventional approach to seismic hazard mitigation is to design structures with adequate strength and ability to deform in a ductile manner. Over the past two decades, newer concepts of structural vibration control including seismic isolation, installation of passive and active/semi-active devices (Soong (1988), Jangid and Datta (1995), Nagarajaiah (1997), Ehrgott and Masri (1994)) have been growing in acceptance. Traditionally, earthquake-resistant design of low- to medium-rise buildings is particularly important, as their fundamental frequencies of vibration are within the range where earthquake-induced force (acceleration) is the highest as found during Mexico City Earthquake (Kelly (1990)). One possible mean to reduce the degree of amplification is to make the building more flexible (Paulay and Priestley (1992)). In a low-to-medium-rise building, this necessary flexibility can be achieved by the use of base isolation techniques.

The primary mechanism for the reduction of shaking level in a base isolation method is energy dissipation. The concept of low-cost and effective earthquake protection techniques using natural material like sand was looked at by Qamaruddin and Ahmad (2007), Qamaruddin et al. (1992) and Feng et al. (1993). The use of a synthetic liner consisting of an ultra molecular weight polyethylene nonwoven geotextile, placed in the foundation of a structure, was also found to be an effective way of reducing seismic ground motion by Yegian and Kadakal (2004), and Yegian and Catan (2004). Soil reinforced with rubber demonstrates a tremendous increase in energy dissipation capability (Edil and Bosscher (1994)). The feasibility of using shredded rubber mixed with sand as a natural base isolator was investigated theoretically by Gray et al (1996) and Tsang (2008). This paper presents results of experimental investigations into the performance of a layer of sand and composites like sand mixed with various proportions of shredded rubber tire as low cost base isolation systems.

EXPERIMENTAL SETUP

The laboratory model tests are performed on a 1m by 1m shake table. The table is shaken in a uniaxial horizontal direction by specifying a sinusoidal motion of given amplitude and frequency. The details of the shake table and its calibration can be found in Giri and Sengupta (2009). In the laboratory model tests, the building foundation or footing is assumed to be square and modeled by a 200mm by 200mm and 40mm thick, rigid plexi-glass block. The surcharge load (normal load) on the foundation due to the super structure is imparted by a number of steel plates (weights) bolted on top of the plexi-glass block. In all the cases, the surcharge load is 15kg. A coarse sand paper is glued to the bottom side of the block to model the roughness of the model footing. In the laboratory shake table tests, the model footing is placed inside a 1000mm by 1000mm and 500mm high, open plexi-glass container or tank. The plexi-glass container is made up of 12 mm thick plexi-glass sheets and reinforced with steel angles at all the corners and edges. About 30mm thick thermocol sheets are glued to all the sides of the container except one to minimize the reflection of waves at the ends. One side of the plexi-glass container is kept clear to monitor the behavior of the model footing during a test. The whole setup is placed on top of the shake table and securely clamped to it to ensure no relative movement. The test container is then filled with sand up to 200mm height and compacted to the required density. Details of shake table arrangement are shown in Figure 1 below.

Figure 1. Shake table test setup.

The first series of tests are performed with the model footing placed on top of the sand layer at the middle of the container. The second series of the tests are performed with composites made of shredded rubber tire and sand in different proportions as base isolator under the model footing. Before these second series of tests, a 20mm deep square excavation in the sand of the same size as that of the model footing is constructed. This excavation is then filled with the shredded rubber tire and sand mixture. The model footing is then placed over the shredded tire and sand mixture. Several proportions of shredded tire in the shredded rubber tire-sand mixture have been considered. But only the performances of sand mixed with 20%, 30% and 50% shredded rubber tire have been reported here.

BASE MOTIONS

The shake table along with the experimental setup is shaken in horizontal direction by a sinusoidal motions of amplitude 0.15g, 0.3g, 0.4g, 0.6g and 0.8g. The frequency of the motion is varied from test to test to study the effectiveness of the seismic isolators at different frequency of motion. The different frequencies considered are 1.5, 3.5, and 4.5Hz. For each specified motion, vertical and horizontal acceleration of the shake table in addition to those on top of the foundation sand layer, and on top of the model footing are also recorded. Each of the motions is continued for at least 5 numbers of cycles to ensure the system had reached a steady state condition. A typical input base motion is shown in Figure 2.

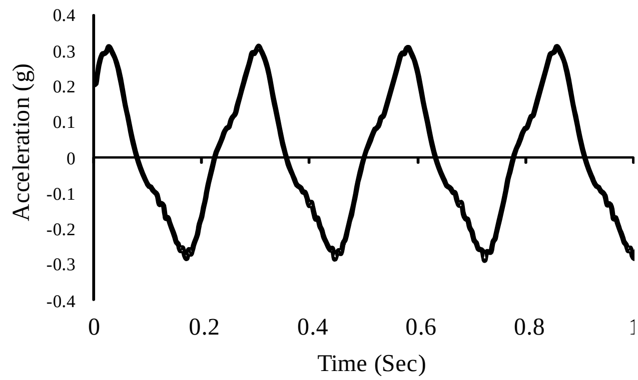

Figure 2. A typical input base motion.

In all the cases, the results for the first few cycles are only shown for the clarity of the presentations. In all the cases, the results for the first few cycles are only shown for the clarity of the presentations.

EXPERIMENTAL RESULTS

<u>Model footing resting on top of foundation sand</u>

The performance of sand as a base isolator has been studied for the given base motions mentioned earlier. In this case, the model footing is resting directly on top of 200 mm deep sand layer within the test tank. The sand used in the study is a local uniform medium sand (Kansai River sand). It is classified as poorly graded sand (SP) as per Unified Soil Classification System. The specific gravity of the sand is 2.7. The maximum and minimum dry unit weights are 16.6 and 14.1 kN/m^3, respectively. In all the tests, the relative density of the sand foundation within the test chamber is maintained at 65%. The shear strength (effective cohesion, c' and effective friction angle, ϕ') of the sand, as obtained from the laboratory direct tests, are given by c'=0 and ϕ' =36^o. Figure 3 shows the transmitted peak accelerations at the top of the footing resting on sand with respect to the peak acceleration of the base motion for different amplitude of motions (keeping the frequency constant at 3.5 Hz). The figure shows that at and around 0.6g amplitude of base motion, the sand beneath the model footing starts to dampen the base motion. This is accompanied by a sliding movement of the model footing. This back and forth sliding movement of the model footing is around 3mm in case of 1g motion of the shake table.

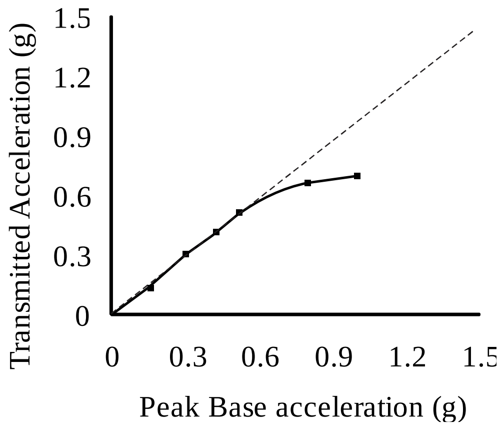

Figure 3. Footing response for different base motions with constant frequency of 3.5Hz.

It is clear from the above figures and tables that the sand layer in the foundation behaves as an effective base isolator only at high amplitude (above 0.6g in these cases) of base motions.

Model footing resting on top of shredded rubber tire and sand

In this case, a 20 mm thick layer of sand and shredded rubber tire mixture is placed between the model footing and the foundation sand layer within the test tank. The shredded rubber tire is obtained from a local shop. The average length of a thread of shredded tire is 10 mm and the average diameter is 1 mm. Figure 4 shows a magnified view of shredded rubber tire and sand mixture.

Figure 4. Magnified view of sand and 50% shredded rubber tire mixture.

Three different proportions (by weight) of shredded rubber tire – 20%, 30% and 50% in sand have been utilized in this study as potential low cost base isolators under the model footing. The direct shear strength of dry sand mixed with various proportion of shredded rubber tire is given in Figure 5.

The shear strength (effective cohesion, c' and effective friction angle, ϕ') of the sand is found to be given by c'=0 and ϕ'=36^{o}. The shear strength of sand mixed with 20% (by weight) of shredded rubber tire is given by c'=0 and ϕ'=34^{o}.

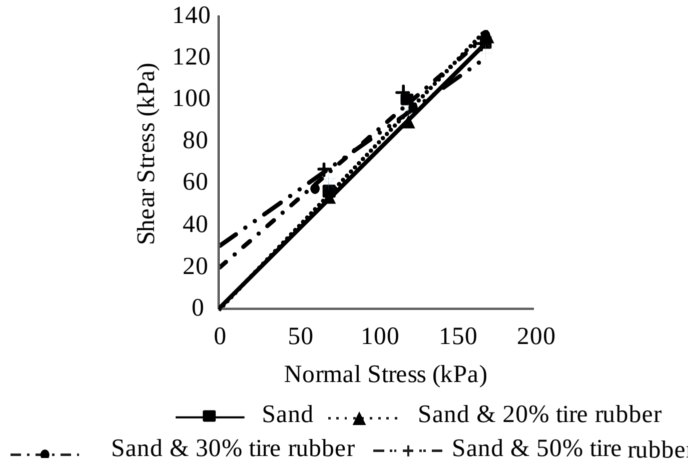

Figure 5. Results of direct shear tests on sand and shredded rubber tire mixtures.

The same for sand with 30% shredded rubber tire is c'=20kPa and ϕ'=32^{o}. The shear strength for sand with 50% shredded rubber tire is found to be c'=30kPa and ϕ'=30^{o} from the above figure. Thus the effective cohesion of the sand-shredded rubber tire composite is found to be increasing while the effective friction angle is decreasing with the percentage increase in shredded rubber tire.

Before the shake table tests, a 20 mm deep square excavation in the sand of the same size as that of the model footing is constructed. This excavation is then filled with the shredded rubber tire and sand mixture in correct proportion. The model footing is then placed over the shredded tire and sand mixture (Figure 6). As done for the previous cases, in this case also the whole test setup is shaken on the shake table for the previously stated sinusoidal motions.

Figure 6. Model footing resting on shredded rubber and sand mixture.

Model footing resting on top of 20% shredded rubber tire and sand

The comparison between the peak acceleration at the top of the model footing resting on sand mixed with 20% of shredded rubber tire and the peak acceleration of the input (measured during the tests) base motions for a base motion of amplitude 0.3g and frequency 3.5 Hz are shown in Figure 7.

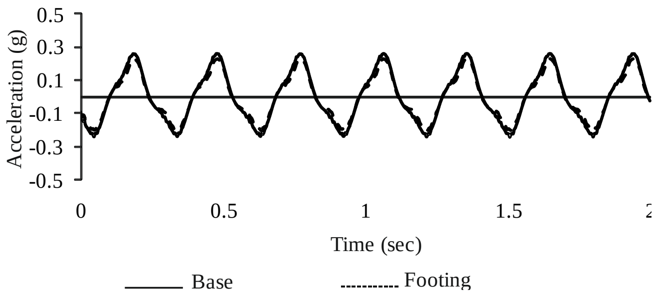

Figure 7. Footing response to a 0.3g amplitude and 3.5Hz frequency base motion.

The footing response to various frequencies of motion keeping the amplitude at 0.3g is shown in Table1. Table 2 shows the response of the footing to various amplitude of motion keeping the frequency constant at 3.5Hz.

Table 1. Variation of peak acceleration at the top of footing and shake table for different frequencies of base motions with constant amplitude of 0.3g.

Frequency(Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
1.5	0.3	0.29
2.5	0.3	0.30
3.5	0.3	0.31
4.5	0.3	0.28

Table 2. Variation of peak acceleration at the top of footing and shake table for different amplitude of base motions with constant frequency of 3.5 Hz.

Frequency (Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
3.5	0.15	0.16
3.5	0.3	0.27
3.5	0.4	0.38
3.5	0.5	0.48

The response of the model footing resting on sand and 20% shredded rubber tire exhibit a little damped behaviour when compared with those for the footing on sand. The effect of frequency is not at all clear in these tests. The displacement of the footing is found to be 1mm for a base motion of magnitude 0.3g and frequency 3.5Hz.

Model footing resting on top of 30% shredded rubber tire and sand

In this case, the model footing is resting on a composite consisting of sand and 30% shredded rubber tire. Figure 8 shows the response of the footing to a base motion of 0.3g and 3.5Hz.

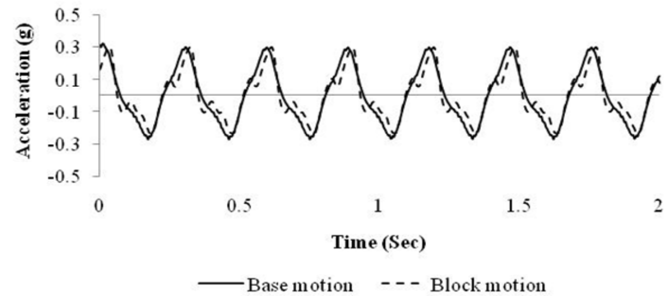

Figure 8. Footing response to a 0.3g amplitude and 3.5Hz frequency base motion.

The footing response to various frequencies of motion keeping the amplitude at 0.3g is shown in Table3. Table 4 shows the response of the footing to various amplitude of motion keeping the frequency constant at 3.5Hz.

Table 3. Variation of peak acceleration at the top of footing and shake table for different frequencies of base motions with constant amplitude of 0.3g.

Frequency(Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
1.5	0.3	0.28
2.5	0.3	0.27
3.5	0.3	0.28
4.5	0.3	0.26

The response of the model footing resting on sand and 30% shredded rubber tire exhibit better behaviour as a base isolator when compared with those for the footing on sand and on sand and 20% shredded tire. The effect of frequency is again not at all clear in these tests. The displacement of the footing is found to be 1.5mm for a base motion of magnitude 0.3g and frequency 3.5Hz. The performance of the base isolator improved significantly at higher magnitude of base motions.

Table 4. Variation of peak acceleration at the top of footing and shake table for different amplitude of base motions with constant frequency of 3.5 Hz.

Frequency(Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
3.5	0.15	0.15
3.5	0.3	0.28
3.5	0.4	0.35
3.5	0.5	0.45
3.5	0.6	0.51
3.5	0.7	0.59

Model footing resting on top of 50% shredded rubber tire and sand

In this case, the model footing is resting on a composite consisting of sand and 50% shredded rubber tire. Figure 9 shows the response of the footing to a base motion of 0.3g and 3.5Hz. The displacement of the model footing during the test is shown graphically in Figure 10. The maximum footing displacement is 1.8mm in this case.

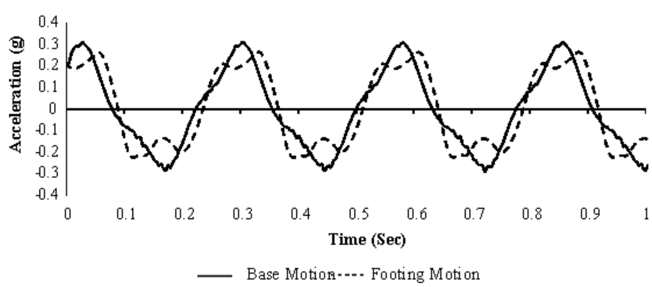

Figure 9. Footing response to a base motion of amplitude 0.3g and frequency 3.5Hz.

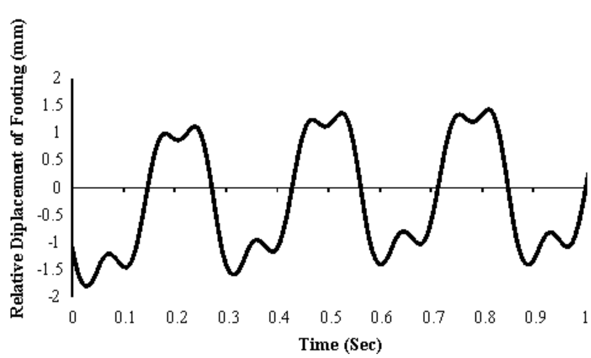

Figure 10. Relative displacement of the footing for a base motion of 0.3g and 3.5Hz frequency.

The comparison of the peak transmitted acceleration on top of the footing is also compared graphically with peak base acceleration in Figure 11.

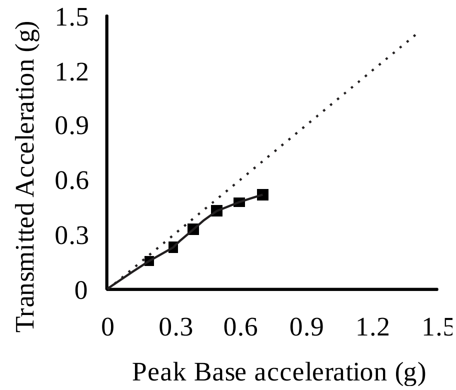

Figure 11. Comparison of the peak transmitted acceleration on top of the footing resting on 50:50 sand-shredded rubber tire mixture.

The test results show that, unlike in sand, even at small amplitude of base motion, the response of the model footing is remarkably less than the original base motion. This indicates that the isolating layer consisting of sand mixed with 50% shredded rubber tire is quite effective in dampening the cyclic motions. Figure 11 attests to the effectiveness of the sand mixed with 50% shredded rubber tire as a base isolator for cyclic motions.

The response of the model footing resting on 50% shredded rubber tire and sand mixture to 0.3g base motions at various frequencies is shown in Table 5. The effect of frequency on the response of the footing is not so clear for these cases also.

Table 5. Variation of peak acceleration at the top of footing and shake table for different frequencies of base motions with constant amplitude of 0.3g.

Frequency(Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
1.5	0.3	0.2
2.5	0.3	0.25
3.5	0.3	0.23
4.5	0.3	0.22

Table 6 shows the response of the footing to base motions of various amplitudes keeping the frequency constant at 3.5Hz. The positive effect of the base isolation is very clear from this table even at small amplitude of motion. The composite consisting of sand and 50% shredded rubber tire is found to yield the best results as a base isolator under the model footing among all the cases looked at in this study. The displacement of the model footing is found to be increasing with the increase in the percentage of shredded rubber tire in the base isolator.

Table 6. Variation of peak acceleration at the top of footing and shake table for different amplitude of base motions with constant frequency of 3.5 Hz.

Frequency(Hz)	Peak Base Acceleration(g)	Peak Transmitted Acceleration(g)
3.5	0.2	0.15
3.5	0.3	0.23
3.5	0.4	0.32
3.5	0.5	0.43
3.5	0.6	0.48
3.5	0.7	0.52

The shake table test conducted with higher than 50% shredded rubber tire in sand shows instability even at very small amplitude of base motion. The model footing with 15kg surcharge load on top starts to wobble at the very initial stage of this test and the test is discontinued.

CONCLUSIONS

The sand in the foundation of the model footing is found to be ineffective as a base isolator at low amplitude (<0.6g) of base motion. However at higher amplitude (> 0.6g) of motion, it is quite effective in reducing the motion transmitted to the footing. At 0.8g and 1g, the accelerations at the top of the model footing show a remarkable decrease and this decrease in response is also accompanied by back and forth displacement of the footing over the sand foundation. At 1g of motion, the amplitude of this displacement is observed to be about 4mm.

The shake table tests with the model footing resting on a 20mm layer of sand and shredded rubber tire show that the proportion of shredded rubber tire should be 50% (by weight) to yield a significant favorable results. When the proportion of the shredded rubber tire is 50%, the response of the model footing is found to be significantly less than the motion of the foundation and shake table. The displacement of the footing during the cyclic motion is found to be increasing with the increase in the percentage of shredded rubber tire in the sand. When the percentage of shredded rubber is increased beyond 50%, the model footing is found to wobble (unstable) at 0.3g motion.

A base isolating system can be effective in two ways- 1) by reducing the input motion that the structure is subjected to, and 2) by shifting the predominent frequency of the structure from that of its base motion, so that resonance of frequency can not be achieved. This paper only addresses the base isolation by dampening of the input motion. Since all the input motions of the shake table are sinusoidal with a given frequency, the shifting of the frequency of the model footing during a test could not be studied. It is hoped to study this important aspect of the base isolation system in the next phase of the study.

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REFERENCES

Edil, T. B. and Bosscher, P. J. [1994]. “Engineering properties of tire chips and soil mixtures”. Geotechnical Testing Journal, ASTM, Vol. 17, No. 4, pp. 453-464.

Ehrgott, R. C. and Masri, S. F. [1994]. “Structural control applications of an electro rheological device”, *Proceedings of the International Workshop on Structural Control*, Univ. of Southern California, Los Angeles, pp. 115-129.

Feng, M. Qing, Shinozuka, M. and Fuji, S. [1993]. “Friction-controllable sliding isolation system”. Journal of Engineering Mechanics, Vol. 119, No. 9, pp. 1845-1864.

Feng, Z. Y. and Sutter, K. G. [2000]. “Dynamic properties of granulated rubber-sand mixtures”. Geotechnical Testing Journal, ASTM , Vol. 23, No. 3, pp. 338-344.

Giri, D. and Sengupta, A. [2009]. “Dynamic behavior of small scale nailed soil slopes”. Geotech Geol. Eng., Vol. 27, pp. 687-698.

Gray, D.-H. and Ohashi, H. [1983]. “Mechanics of fiber reinforcement in sand”. J. Geot. Engg., ASCE, Vol. 112, No. 8, pp. 804-820.

Jangid, R. S. and Datta, T. K. [1995]. “Seismic behavior of base-isolated buildings: a state-of-the-art review”. Proceedings - ICE: Structures & Buildings, Vol. 110, No. 2, pp. 186-203.

Kelly, J. M. [1990]. “Base isolation: linear theory and design”. Earthquake Spectra, Vol. 6, No. 2, pp. 234-244.

Nagarajaiah, S. [1997]. “Semi-active control of structures”, *Proceedings of Structures Congress XV, ASCE*, Vol. 2, Portland, Oregon, pp. 1574-1578.

Paulay, T. and Priestley, M. J. N. [1992]. “*Seismic design of reinforced concrete and masonry buildings*”. Wiley, New

York, New York.

Qamaruddin, M. and Ahmad, S. [2007]. "Seismic response of pure - friction base isolated masonry building with restricted base – sliding". J. Engg. Res., Vol. 4, No. 1, pp. 82-94.

Qamaruddin, M., Arya, A. S. and Chandra, B. [1986]. "Seismic response of brick buildings with sliding substructure". Journal of structural Engineering, Vol. 122, No. 12, pp. 558-572.

Soong, T. T. [1988]. "State-of-the-art review, active structural control in civil engineering". Engineering Structures, Vol. 10, No. 2, pp. 74-84.

Tsang, H. H. [2008]. "Seismic isolation by rubber-soil mixtures for developing countries". Earthquake Engineering and Structural Dynamics, Vol. 37, No. 2, pp. 283-303.

Yegian, M. K. and Catan, M. [2004]. "Soil isolation for seismic protection using a smooth synthetic liner". Journal of Geotechnical and Geo-environmental Engineering, ASCE, Vol. 130, No. 11, pp. 1131-1139.

Yegian, M. K. and Kadakal, U. [2004]. "Foundation isolation for seismic protection using a smooth synthetic line". Journal of Geotechnical and Geo-environmental Engineering, ASCE, Vol. 130, No. 11, pp. 1121-1130.