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A STUDY OF BASE ISOLATION METHOD USING SOIL LIQUEFACTION

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SUMMARY

In this paper, the idea, construction and experimental study of a new isolation method using soil liquefaction is presented. Reports about earthquake hazards and research work in laboratories have indicated that liquefied soil can be used as an isolation material, when some prerequisites are fulfilled. After an experimental study of the soil material, a model of this isolation system was tested on a shaking table. A model describing the behavior of this system is being analysed on the basis of the experiments. The results show an effective isolation of this method. The motivation of studying this method is to obtain an economical isolation system.

1.INTRODUCTION

Generally speaking, soil-liquefaction is almost always a catastrophe during earthquakes. The liquefied soil will be squeezed out of ground under foundation of a building, and this may lead to a large settlement or tilting of the building. However if the change of the volume of soil can be prevented, foundation failure will be avoided and the transmission of the ground vibration into the superstructure will be reduced due to the very low shear stiffness in the liquefied soil. There were cases in which buildings survived earthquake attacks under such natural ground conditions. One of them was in Japan (Ref.1).

2.AN ISOLATION SYSTEM USING SOIL LIQUEFACTION

Based on the above-mentioned idea a new base isolation system is being developed. (Fig.1) (Ref. 2) The superstructure is built on several isolators, which separate it from the foundation. The isolators are filled with a selected mixture of loose soil saturated with water. An impermeable and elastic side wall around the soil keeps its volume constant. According to the results of many soil experiments and an initial analytical study of the feasibility of such a method, there are the following basic characteristics of this isolation method:

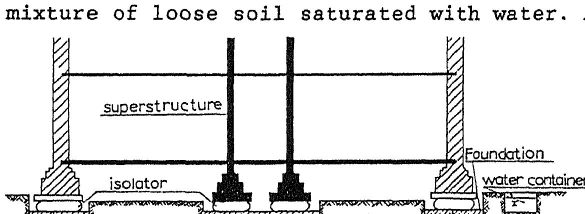


Fig.1 Construction of the Isolation System

a) A loose, uncohasive and saturated soil under undrained condition tends to liquefy after a number of shear loading cycles are applied to it. The higher the loading amplitude and the lower the density of the soil , the less the number of loading cycles needed to cause liquefaction. (Ref.3) That means that the vibration energy input into the soil (and accordingly transmitted into the superstructure) till liquefaction is confined. The soil and its density in the isolator will be so determined that before the transmitted vibration energy can cause any structural damage the soil liquefies. After liquefaction the soil in the isolator has hardly any shear stiffness. The eigenfrequency of the whole system will be shifted to a very low range so that the superstructure will be isolated from strong earthquake attacks.

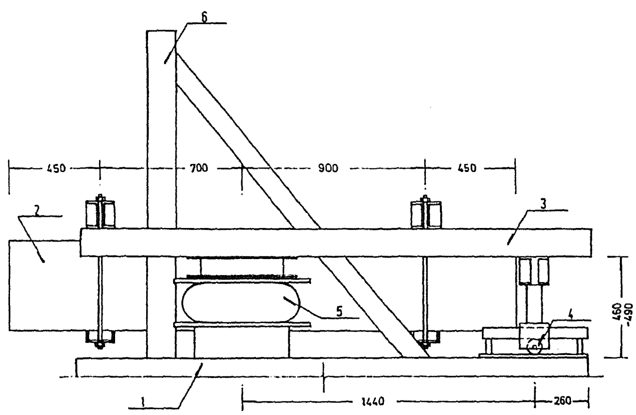
b) By virtue of an impermeable side wall with a suitable geometric form and because of the undrained condition in every respective isolator, the volume and the height of each isolator will not change before and after liquefaction of the soil in the isolator. Therefore, the isolators will keep the bearing capacity and ensure the stability of the superstructure.

c) The soil after liquefaction is a good damping material owing to the friction between soil grains under large shear strain amplitudes.

To get a practically usable soil material and to study its characteristics, experiments have been carried out. During these experiments the above mentioned characteristics of such an isolation method are proved.

3. SOIL EXPERIMENTS FOR A SUITABLE MATERIAL AND ITS CHARACTERISTICS

A suitable soil material for the isolators was at first searched and tested. "Suitable" means that the soil should liquefy in a few cycles under strong shear loading but it should not change its characteristics under weak shear loading or vibrations. That is to say, soil in the isolation system does not tend to liquefy during weak earthquakes which will not cause any structural damage. Besides, the filling of isolators with soil with a certain density will not be difficult. Soil experiments done by many researchers have made it possible to find such a soil material. (Ref.4) Tests for the suitable soil material were done with a double simple shear triaxial device. The experimental study of its characteristics was done with a large scale simple device as well as through shaking table tests. (Ref.5) (Fig.2)



1. Shaking Table
2. Mass
3. Supporting Element
4. Rolls
5. Isolator
6. Measure Frame

Fig.2 Shaking Table Test for Study of Soil Material

The tests for soil material show that a saturated fine Rhein-sand (standard test sand in West Germany) with relative monotone grain-size distribution as well as the Montergy No.0 sand in an undrained condition will liquefy quickly enough under strong shear cyclic loading, when the density of the sand is kept less that 30%. But the sand in such a density is very sensitive to vibrations, since the grain structure of the soil tends easily to be in a denser situation even under weak vibration. That means the density of such sand alone can not be kept stable even during construction phase and under weak ground vibration. Therefore a mixture of the sand with a bentonite (tixoton) material was developed for the practical isolation system. The behavior of such a mixed soil material in the further tests showed that the characteristics of the mixed soil were stable despite of the fact that the filling of the isolator element with soil was difficult. Apart from this, there was an observable threshold value of the soil. The mixture will be one of the suitable materials for this isolation system.

After the soil material was selected, tests for its characteristics were carried out. The tests with the simple shear device were done staticly, deformation-controlled and cyclically. Every specimen was tested in several loading steps until the soil liquefied. The shear deformation cycles in tests were harmonic and began with a small amplitude. The amplitude increased in every next loading step. The specimen had a rectangular section of 200 cm^2 and a height of 2.1 cm. The vertical pressure on the soil and the density of the soil were varied . On the basis of the results of simple shear tests, dynamic experiments with soil mixture in isolator model were conducted. The isolator model was made out with a scale of about 1:5 to practically usable prototype of isolators. The isolator model had a round section of 0.2 m^2 and a height of 0.18 m. The mass on the top of the isolator model brought not only vertical pressure but also shear loading to the soil in the isolator, which will be the similar case in the real system. Every specimen was tested in several loading steps with gradually increasing amplitudes until the soil liquefied. The shear loads were harmonic with frequencies between 0.5 to 2 Hz. After the first liquefaction of the soil in the isolator, the specimen was drained and the soil reconsolidated in a denser condition. Then the specimen with higher density was tested again under undrained condition. Such process was able to be repeated two to three times with every test specimen.

The results from the material tests were analysed. Furthermore, the following mechanical characteristics of soil in isolator elements are being studied in order to acquire a mathematical description of the behavior of the isolation system.

a) Liquefaction of the soil

This characteristic of soil liquefaction can be demonstrated through the increase of pore pressure or decrease of effective pressure on the grain structure in every loading cycle β^*. (Ref.5,6) It depends on the intensity of loading and the density of soil. Fig.3 shows the relationship between β^* and shear strain. As a result of the increase of pore pressure till soil liquefaction, Fig.4 shows the relationship between shear stress level (τ/σ'_v) and loading cycles needed to cause liquefaction. It shows that the difference of loading cycles needed to cause liquefaction between low and high shear stress levels is very great. When the loading level is high, the soil will liquefy in only a few loading cycles. However when the strain is smaller than 10^{-4}, there is no change of pore pressure. In other words, this is the threshold value of the soil mixture.

b) Shear strength of the soil

The shear strength of the soil depends on its effective pressure (Mohr-Colomb's failure condition) and on the density of soil. The shear stress-shear strain relationship shows that the maximum stress level was reached when the shear strain was large (over 10^{-2}) (Fig.5). Fig.6 shows the relationship between the maximum shear stress level and pore volume of soil which describes the density of the soil. It is known from the analysis that the maximum shear stress level reduces with the density, but only to a limited degree. Therefore the soil in isolators does not need to be made too loose.

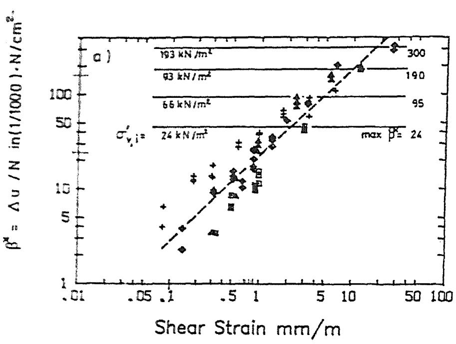


Fig.3 Increase of Pore Pressure vs. Shear Strain

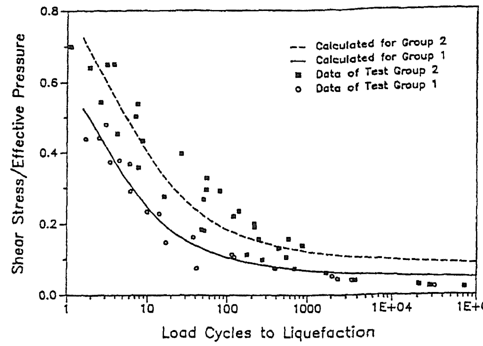


Fig.4 Shear Stress Level vs Loading Cycles to Liquefaction

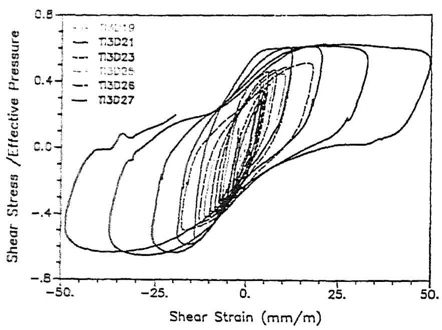


Fig.5 Hysterese of Shear Stress Level vs. Shear Strain

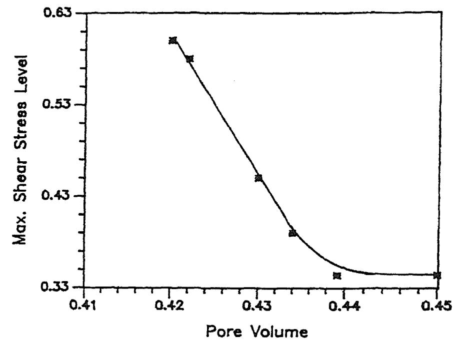


Fig.6 Max. Shear Stress Level vs. Pore Volume of Soil

c) Stress-strain relationship and characteristics of energy dissipation

Fig.5 shows that the soil mixture is a strong nonlinear material. After arriving the maximum stress level the energy will be strongly dissipated due to the plastification of the soil. At this stage, these characteristics will be modeled by an equivalent linear shear modul, which decreases with the increase of shear strain. The energy dissipation will be modeled by an equivalent damping ratio, which increases with the shear strain. Fig.7 and 8 show the results of the modeling of these equivalent parameters.

4. EXPERIMENTAL STUDY OF THE BEHAVIOR OF SYSTEM MODEL

On the basis of the analysis and modeling of the results of material experiments, the behavior of isolation system model was experimentally studied. The test set-up was developed from the test set-up of isolator model. (Fig.9) A model of superstructure with one mass was built on the isolator, so that the isolation effect and interaction between the superstructure and isolator could be demonstrated. With very flexible steel columns the eingenfrequency of the system was modeled one to one. The dynamic characteristics of the whole system was also modeled one to one. The isolated system was tested with several recorded ground accelerations with different features. As comparison, the same model of superstructure without isolators was tested with the same ground vibrations. Fig. 10 shows the reaction of the superstructure model with and without isolators under a similar earthquake excitation.

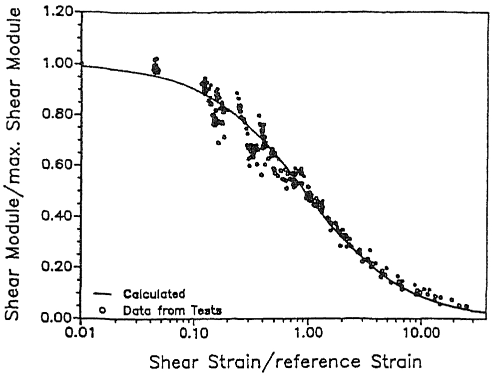


Fig.7 Equivalent Shear Modul vs. Shear Strain

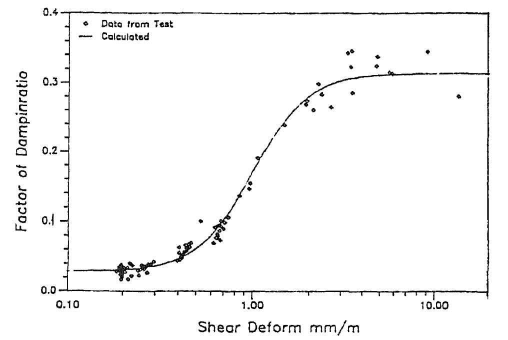
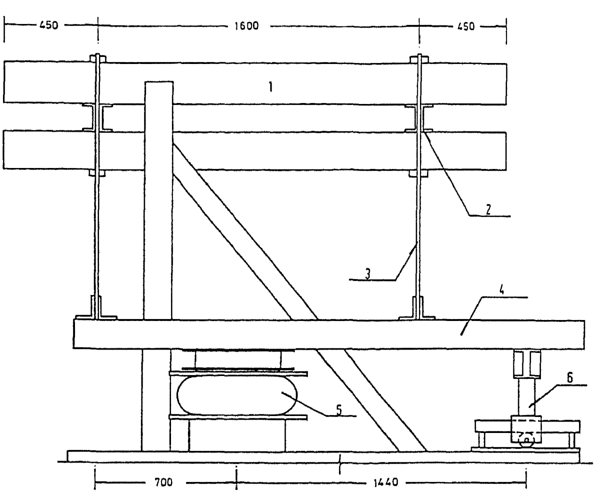


Fig.8 Equivalent Damping ratio vs. Shear Strain



1. Shaking Table
2. Structural Model
3. Column
4. Supporting Element
5. Isolator
6. Rolls

Fig.9 Test Set-up of System Model

From the comparison of the test results of systems with and without isolation the following points can been seen clearly:

a) The maximum response of the isolated structure model is reduced considerably (to 20% to 30%).
b) The energy input into the structure model is greatly reduced (to 1% to 30%).
c) The stability of the structure of the isolation system has been proved.

5. CONCLUSION

The experimental and analytical study of the isolation method using soil liquefaction has proved the feasibility of this method. The material used comes directly from nature. The construction of this isolation system is easy and maintenance is hardly needed. Therefore, it can be expected that this method will be an economical approach towards base isolation. Further study should be done on some technical details and practical design method is to be developed before this method can be put into real usage.

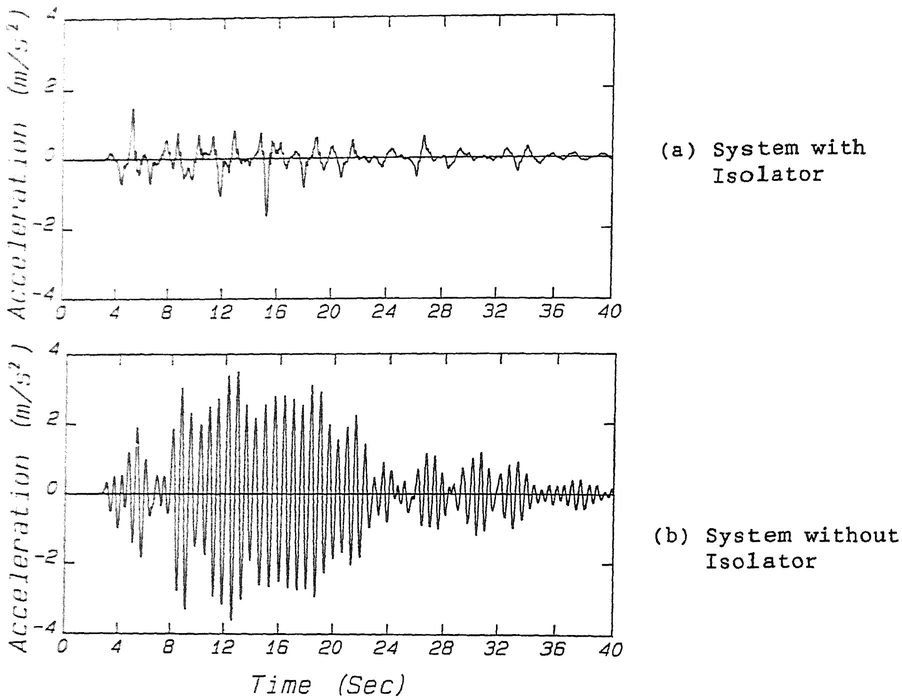


Fig.10 Top Acceleration of structural Model (Excitation: ELCENTRO)

REFERENCES:

1. Kelly, J.M.: Control of Seismic Response of Piping Systems and Other Structures by Base Isolation; Report No UCB/EERC-81/01, Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, California, (Jan. 1981)

2. Tang, S. König, G. & Kroggel, O.: A New Method of Base Isolation against Earthquake Damage Using Natural Material, Transactions of The 9th International Conference on Structural Mechanics in Reactor Technology, Lausanne,(Aug.1987)

3. Shannon & Wilson, Inc.: Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests; U.S. Department of Commerce National Technical Information Service, (May 1975)

4. Dobry,R. Stokoe II, K.H. Ladd, R.S. & Youd, T.L.: Liquefaction Susceptibility from S-Wave Velocity, Preprint 81-544, ASCE National Convention, St. Louis, Missouri, KSCE, New York, New York (Oct. 1981)

5. König, G.: Kostengünstige Bauwerksisolierung gegen Boden-Erschütterung durch Gezielte Nutzung der Bodenverflüssingung, Abschlußbericht, (1988)

6. Bjerrum,L. Geotechnical Problems Involved in Foundations of Structures in the North Sea, Geotechnique 23, No.3 p.319-358.(1973)