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A DIDACTIC INTRODUCTION TO MODELS AND DEVICES TO MITIGATE SEISMIC ACTIONS

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Abstract. In this didactic paper basic concepts of seismic isolation are discussed. Models and devices of isolating structures to mitigate seismic actions are presented. As an application an easy example is illustrated in the case of a single degree of freedom (SDOF) structure, showing as basic knowledges of mathematics are fundamental to formulate and solve problems in different fields of applied sciences, as seismic engineering. The aim of this paper is to give a simple lecture on techniques used to prevent the effects of an earthquake in a country.

1. Introduction

The aim of this paper is to give a lecture on the most effective technique to mitigate the effect of seismic action, consisting in the "isolation base" and generally realized by some device. A seismic event is manifested by the vibrations induced by the movement of the ground. It generates in a structure inertia forces, each given by the product of a mass by its acceleration. To avoid structural damages during an earthquake, it would be necessary to increase the resistance of a structure proportionally to the intensity of the earthquake. The underlying principle of seismic isolation it is to avoid the earthquake, rather than to resist it. This principle is applied decoupling the dynamic response of the building from the ground motion. Decoupling is obtained through the interposition of devices between structure and foundations, with low horizontal stiffness and high dissipative behavior in order to provide a lower fundamental frequency of the structure and to increase the overall damping of the structure. The organization of this paper is the following. In Section **2** we illustrate the didactic method used in this paper to introduce different models and devices to mitigate the seismic action. Sections **3** and **4** concern a panoramic on the historical development of the basic principles of seismic isolation in the past years and the description of some applications in the buildings in ancient civilizations. Since the city of Messina strongly suffered the effects of a disastrous earthquake in 1908, the subject will be certainly of particular interest for an increasing number of scientist and engineers in the domain of the scientific divulgation. In section **5**, a simple application is treated, by which the mathematics education is encouraged, as through the knowledge of mathematical procedures

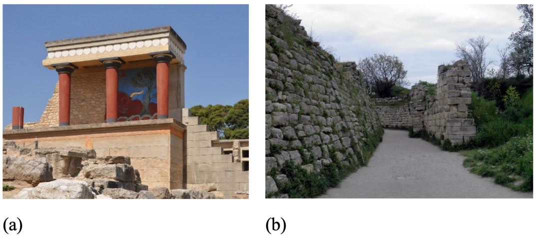


FIGURE 1. First applications of seismic isolation: (a) Cnósso Palace, (b) Troia's walls.

it is possible to solve difficult seismic engineering problems. A problem, still open, is to find new models, consisting in the postulation of different equations for the seismic isolation. As a consequence, new devices arising from the study must be adopted for attenuating the effect of earthquakes

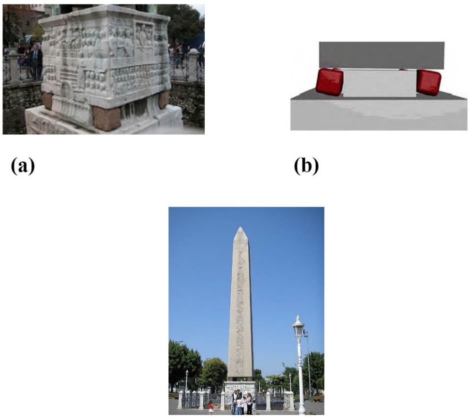
2. Didactic method

In this paper a classic didactic approach is used to present in a simple way different models and construction techniques applied in the history of seismic engineering to contrast the effects of seismic actions. Foundations and historical developments of seismic isolation are exposed. Basic principles of ancient and modern formulations are presented to give a simple lecture on this subject of engineering science. An easy application is given showing as the mathematical procedures are very important in applied sciences and encouraging the students to learn mathematics and its strategies to develop models and methods to represent physical phenomena and to solve seismic engineering problems.

3. Historical development of base isolation system

Historical studies and archaeological campaigns have revealed that ancient civilizations were facing the problem of building structures that could resist to an earthquake. Important buildings of many ancient civilizations have survived several earthquakes, even of big magnitude. It seems that over 2000 years ago, builders had realized the importance of inserting "elements" that had the property of attenuating the effect of earthquakes. In ancient Crete (2000-1200 b.C.) it is possible to find symmetrical buildings consisting of monocellular nuclei (see Figure 1 (a)). The structure was made up of stone blocks interconnected by wooden elements which, in addition to ensuring the connection between the elements, provided "plasticity" to the entire building, compensating for the "fragility" of the stone. These buildings were also resting on a layer of sand and gravel that, apart from smoothing soil irregularities, produced a filtering action against soil vibrations during an earthquake. Under the foundations of the Troy walls (1500 b.C.) (see Figure 1 (b)), according to U.S. archeologist Carl Blegen, a layer of compact earth between the foundation plan and the base rock was deliberately left. According to the archaeologists, the builders wanted to create a ground cushion in such a way as to protect the wall from the effects of an earthquake.

In ancient Greece the idea of protecting the structure was widespread by disconnecting it from the ground, interposing between it and the foundations some layers of material that could "translate" the construction against the ground in the event of an earthquake. In some cases they lay under the firm foundation of ceramic and clay layer walls. The ceramic protected the clay layer from moisture and dehydration, maintaining the plastic properties that dampened ground vibrations during an earthquake. Archaeological excavations have shown that trenches wider than the sizes of the foundations were excavated for substrutures, and a layer of 20 cm thick limestone gravel was laid on the ground. On this layer the walls were raised and the lateral voids were filled with waste material from stone processing. It is important to note that the material was not used again for filling. In this way the foundation walls were insulated and lined on all faces, from the wet ground. In antiquity another example of seismic isolation is the Dikilitash obelisk located in Turkey (see Figure 2: (a), (b), (c)). It is a stone block of 18.69 m high, carved in Egypt in 1450 b.C and was erected in Instabul in 379-395 a.C. It is mounted on a marble base of 3x3x3 m^3 through 4 cubes (50x50x50 cm^3) of bronze placed in the edges. It has been calculated that it can collapse by an earthquake of magnitude greater than 7.6 and having an epicenter at a distance of 5 km.



(a) **(b)**

(c)

FIGURE 2. Dikilitash obelisk: (a) base of the real structure, (b) base model, (c) real structure.

There are certain references to a primal application of isolation to the base also in Kyoto for Sanjusangendo, a Buddhist temple built in 1266 a.C., containing a famous building built to accommodate 1000 statues (see Figure 3). Below the foundations were laid layers of coal, woolen yarns, sand, so that it could favor the sliding of the structure with respect to the ground. The temple did not suffer damage following the 1995 Kobe earthquake (only 4 statues were slightly damaged).

FIGURE 3. Temple of Sanjusangendo.

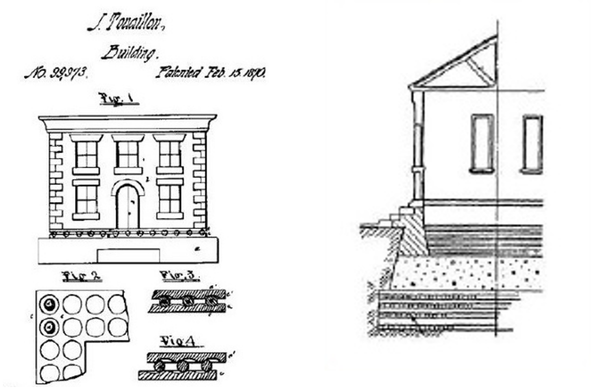
4. First patents on isolation

In 1870 we have the first document, due to Jules Touaillon (1870), attesting to the idea of designing a building with a system that decouples the motion of the structure from the ground (Figure 4 (a)). The patent was based on the use of spheres interposed between the foundation of the structure and foundations, but never had any practical application. More than a century ago, in 1885, John Milne, a professor of engineering in Japan, built a small wooden house on balls in cast-iron plates with saucer-like edges on the heads of piles, to demonstrate that a structure could be isolated from earthquake shaking (see Milne 1885; Housner *et al.* 1997). However, the building behavior under wind loads was not satisfactory. So, he reduced the balls diameter from 10 inch to 1/4 inch. By this mean, the building became stable against wind loads and was evidently successful under actual earthquake action. In 1891, after Narobi earthquake, the Japanese Kawai, proposed a base isolated structure with timber logs placed in several layers in the longitudinal and transverse direction (Figure 4 (b))(see Izumi 1988)

In 1906, Jacob Bechtold from Germany applied for an U.S. patent in which a seismic-resistant building has to be placed on rigid plate supported on spherical bodies of hard material (Figure 5 (a)) (see Buckle and Mayes 1990).

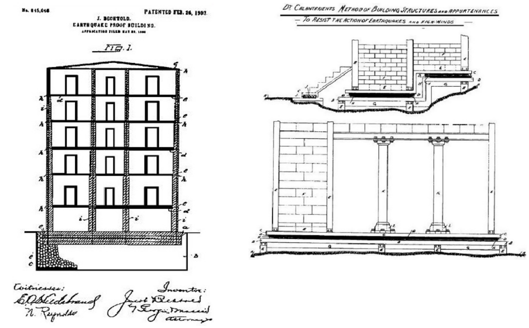
In 1909, a medical doctor from England, Calentarients, had submitted a patent application to the British patent office for a method of building construction. In his method, a building is constructed on a layer of fine sand or talc that would allow the building to slide in an earthquake, there by reducing the force transmitted to the building itself (Figure 5 (b)) (see Kelly 1990).

He also invented ingenious connections for gas and sewer networks, so as to avoid damage during ground vibrations. A patent that never had a practical application. Following the earthquake of 1908, resulting in a tsunami that hit Messina and Reggio Calabria causing between 80,000 and 120,000 deaths and the collapse of 90 percent of Messina's buildings, the City Reconstruction Commission proposed two intervention techniques that provided for decoupling the building from the foundations by inserting a layer of sand or rollers under the columns that allowed the building to move horizontally. The second one was



(a) (b)

FIGURE 4. First patents on isolation: (a) Touaillon, (b) Kawai.



(a) (b)

FIGURE 5. Other first patents on isolation: (a) Bechtold, (b) Calentarients.

recommended between the two approaches. Unfortunately, these proposals were never accepted.

In 1911, the scholar Domenico Lodá invented the first "seismic isolator" in history. This patent provided a support system that prevented the transmission of seismic movements and anticipated modern isolator solutions. This device can be considered as the ancestor of current isolators. Simultaneously to the development of the soft first-story approach, the flexibility of natural rubber was also seen to be another solution for increasing the flexibility of the system. The first use of a rubber isolation system was in 1969 to protect a structure from earthquake, and it was an elementary school in Skopje, Yugoslavia. The Pestalozzi School (see Figure 6), a three story concrete structure designed and built by Swiss engineers, is isolated by a system known as the Swiss Full Base Isolation-3D System (Staudacher *et al.* 1970). The rubber bearings used in this application were completely unreinforced so that the weight of the building causes them to bulge sideways. To improve the building stability under minor vibrations, glass blocks acting as seismic fuzes are intended to break when the seismic loading exceeds a certain threshold. Owing to have the same stiffness of the isolation system in all directions, the building bounces and rocks backwards and forwards (Jurukovski and Rakicevic 1995). Because of this the adoption of these devices turned out to be unsatisfactory and they were no longer used in other applications.

FIGURE 6. The Pestalozzi School.

Seismic isolation became a reality in the seventies in England, where the first elastomeric bearings by the MRPRA (Malaysian Rubber Producers' Research Association) were produced, who devised a process for vulcanizing rubber layers with a stainless steel. These bearings are very stiff in the vertical direction to carry the structural weight but they are very flexible horizontally to enable the isolated structure to move laterally under strong ground motion. The first application was made in France in the early 70s, in order to safeguard a series of nuclear power stations and plant facilities. The utility developed a standard nuclear power plant with the safety grade equipment qualified for 0.2 g acceleration. The system combines laminated neoprene bearings with lead-bronze alloy in contact with stainless steel, the sliding surface being mounted on top of the elastomeric bearing. The coefficient of friction of the sliding surface is supposed to be 0.2 over the service life of the isolator (Electricité-de-France System). In the early 80s, developments in rubber technology led to new rubber compounds which were termed high damping rubber (HDR) (see Derham C. and Tomas 1985). In the 80s the seismic isolation technique spread throughout the world with important applications in bridges and strategic buildings, especially in the U.S. and New Zealand, elastomeric isolators with high damping rubber using high dissipation (High Damping Rubber Bearing) or isolators with lead plug, Lead Rubber Bearing (LRB) (see Tarics *et al.* 1984; Charleston *et al.* 1987; Reaveley *et al.* 1998); in Japan the solution initially more adopted involved the use of low-damping elastomeric devices, Low Damping Rubber Bearing (LDRB) with the addition of viscous or hysteretic dampers. Later, a large number of isolation devices were developed including rollers, springs, friction slip plates, capable suspensions, sleeved piles, and rocking foundations. Now seismic isolation has reached the stage of gaining acceptance and replacing the conventional construction, at least for important structures. Moreover, after the two catastrophic events such as the 1994 Northridge and the 1995 Kobe earthquake, which struck respectively California and Japan, the development of seismic isolation had an additional input. Indeed in those events the isolated structures turned out to be performance higher than that one of the equivalent fixed base structures located in the same affected area.

After these events, the number of applications of seismic isolation has undergone considerable development particularly in Japan. The interest for this application is remarkable in existing buildings, in which the seismic isolation can reach levels of security significantly higher than those achieved by the traditional type of retrofitting. In USA the first examples of seismic retrofitting of existing buildings by basic isolation go back to the mid-90s. The structures were large buildings such as City Hall in Oakland, San Francisco and Los Angeles. In all above cases rubber devices have been used with lead plugs or high damping bearing (LRB or HDRB). Recently, important applications of sliding isolators with curved (see Amin and Mokha 1995) or flat surface have been applied in the U.S.A., with the addition of auxiliary devices re-centering rubber (see Way and Howard 1990) In the last 40 years in Italy, expecially after the earthquake in Friuli (1976) where the viaduct Somplago, protected with a seismic isolation system relatively simple but effective, was the only viaduct without damage, the use of seismic isolation has experienced a constant development. In particular in the decade from 1983 to 1993 seismic isolation was widely used in Italy for the protection of highway bridges and viaducts (see Medeot 1991). For this reason, important national and international research programs, involving companies, research institutes and Italian universities, have been carried out in order to develop the efficacy of the seismic devices and new technologies for devices and isolation systems. Seismic isolation has been studied at different scale levels and for different devices. In the last years dynamic tests on isolators individual small-scale (see Kelly and Quiroz 1992) and real scale, or the performance of dynamic shaking table tests on scale models of isolated structures have been carried out (see Dolce *et al.* 2001, 2008).

5. An example of base isolation technique

The most effective technique to mitigate the effect of seismic actions is the base isolation, generally realized by some device. The vibrations induced by the movement of the ground generate in the structure forces inertia, each given by the product of a mass by its acceleration. To avoid structural damage during an earthquake, it would be necessary to increase the resistance of the structure proportionally with the intensity of the earthquake. The underlying principle of seismic isolation is to avoid the earthquake rather than to resist. This principle is applied decoupling the dynamic response of the building from the ground motion. This decoupling is obtained through the interposition of devices, between the structure and the foundations, with low horizontal stiffness and high dissipative behavior to provide a lower fundamental frequency of the structure and to increase the overall damping of the structure.

The linear theory of seismic isolation is provided in detail in Kelly (1990). The characteristic aspects of the dynamic behavior of base isolated structures can be derived from the analysis of a simplified model, where the frequencies of an isolated single degree of freedom (SDOF) structure are evaluated. The equations of the motion of this structure in this easy example are the following:

$$m\ddot{u}(t)+m\ddot{u}_b(t)+c\dot{u}(t)+ku(t)=-m\ddot{u}_g(t), \tag{1}$$

$$m\ddot{u}(t)+m_{tot}\ddot{u}_b(t)+c_b\dot{u}_b(t)+k_b u_b(t)=-m_{tot}\ddot{u}_g(t), \tag{2}$$

where $m\ddot{u}_g$ is associated with the ground motion, u, $\dot{u}$ and $\ddot{u}$ are, respectively, the displacement, velocity and the acceleration of the significant degree of freedom (D.O.F.) of the structure, u_b, $\dot{u}_b$ and $\ddot{u}_b$, are the displacement, the velocity and the acceleration of the base isolation system, all functions of time t; m, c, k are respectively the mass, the damping coefficient and the stiffness of the single degree of freedom of the structure and m_b, c_b, k_b are the mass, the damping coefficient and the stiffness of the base isolation system. The total mass m_{tot} is defined as follows:

$$m_{tot}=m_b+m.$$

The natural frequencies can be calculated by solving an eigenvalues problem defined by equations (1) and (2). We put

$$\omega_0^2=\frac{k}{m},\quad \zeta_0=\frac{c}{2\sqrt{km}},\quad \omega_{iso}^2=\frac{k_b}{m_{tot}},\quad \zeta_{iso}=\frac{c_b}{2\sqrt{k_b m_{tot}}},\quad \gamma=\frac{m}{m_{tot}}.$$

Assuming that $\omega_{iso}^2 \ll \omega_0^2$ the equations lead to the following characteristic equations:

$$\omega_1^2\equiv\omega_{min}^2\simeq\omega_{iso}^2\left(1-\gamma\frac{\omega_{iso}^2}{\omega_0^2}\right),$$

$$\omega_2^2\equiv\omega_{min}^2\simeq\frac{\omega_0^2}{1-\gamma}\left(1+\gamma\frac{\omega_{iso}^2}{\omega_0^2}\right).$$

Taking into account that $\omega_{iso}^2/\omega_0^2 \ll 1$ and that $\gamma < 1$, it can be seen that the first frequency of the isolation-SDOF system is close to the frequency of the isolation system and that the second frequency is greater than that of the SDOF due to the presence of the basement. This implies that the fundamental mode is associated with the isolation system and this can be designed to reduce stress on the structure.

Many models and devices of the last years are inspired to previous results that we have presented in this section. It is interesting to note that this research field is still open, since there is a big variety of devices suggested by the proposed models, that must be realized by utilizing innovative and successful methods and materials. A new model is studied by PhD thesis of Failla (2018).

6. Conclusions

In this lecture foundations and historical developments of seismic isolation, to contrast effects of seismic actions, are exposed in simple way. Learning mathematics is encouraged, as the formulation of models and methods to solve the siesmic engineering problems requires knowledges of mathematical procedures. As a seismic event is manifested by the vibrations induced by the movement of the ground and generates in the structures forces inertia, to avoid structural damage during an earthquake, the underlying principle of seismic isolation consists in preventing the earthquake, rather than to resist it. Since the city of Messina suffered the effects of a disastrous earthquake in 1908, the paper is has interest in the domain of the scientific divulgation, promoting the applications of mathematics in different fields of applied disciplines.

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