Application of Ancient Earthquake Resistant Method in Modern Construction Technology

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SUMMARY
Ancient structures that are still standing reveal the application of some engineering concepts that have been adapted in their construction. Looking at the existing historical structures situated in earthquake prone areas can be a key to this idea. Saint Sophia Mosque, Dikilitash or Ormetash Obelisks in Istanbul are just samples that were investigated by the authors to have such seismic resistant mechanism. To prove such resistance against earthquake, some strong evidence of such idea should be observed. Some detailed investigations show that the seismic resistant method used in the past was in such a manner that the earthquake forces should be prevented from entering to the structure. This means that there should be some sort of isolation in order to make such mechanism work. Seismic isolation in modern construction is generally applied by rubber bearings or other types of rolling systems that prevents significant amount of earthquake forces to enter the structure. However, it should be noted that seismic isolation is not an energy absorbing mechanism; rather it is an energy passing through system. In other words, energy is not dissipated but passing through the isolation levels. As an example, the three layer stone system under the Ormetash Obelisk has such a mechanism. According to the Bible, this system was applied to a tomb for worshiping God in Jerusalem by Cyrus the Great, King of Persia in 550 B.C. The earthquake waves approaching the structure first hit the three layer stone and become completely vertical. In this layered system no mortar is used and allows the waves to play in it. Vertical movement and horizontal motion together make a mechanism to prevent earthquake main shock passes through the structure. This mechanism is governed by a system that is called ratio of acceleration coefficient to that of friction coefficient. This paper explains the details of the analytical procedure to prove why layered cut stones have prevented seismic waves to enter the structures in ancient structures. Finally, it concludes the possibilities of application of that method in modern construction technology.

Keywords: Ancient earthquake resistant method, Base isolation, Earthquake resistant construction

1. INTRODUCTION

Historical structures that are still standing should bring to one’s mind that how they could be well designed specially in earthquake prone areas. They should have a comprehensive engineering system either in superstructure or substructure. In the beginning of 20th century steel and concrete were entered to modern building structures, thus the engineering concept of masonry systems were completely forgotten in most countries. On the other side, the engineering design of German construction technology was distributed around the world in the same era. As it is known, Germany and most other European countries are not located in seismic area. Therefore, such structural technology that was transferred to many countries were not well designed against earthquake and caused so many casualties during the 20th as well as 21st centuries. An example is the 1999 Izmit, Turkey earthquake that caused a complete collapse or heavy damage to 20,000 buildings.

Another reason that one can claim is the experience for modern structures which is not more than a century old, but for ancient structures is over 40 centuries. In some certain places in Anatolia, in different periods, the earthquake protective structural systems were forgotten for several centuries and because of that the structures that were constructed in those periods are not present today.

The scope of this study is to investigate and prove the systems of substructures or foundations that were designed to protect the structures in the past. However, superstructures are not considered here. Some structures that are located in the Anatolian area are taken into consideration for investigation.

The main concept in historical earthquake protection was to stop seismic waves to enter to structures. In other words, it was the application of base isolation concept which was used in construction of historical structures. This reveals that base isolation is not a new concept; rather, application of its principle goes back to ancient times. Several isolation techniques are known to be used in earthquake resistant construction in the past. Among others were construction on multi-layered cut stones, installing pieces of woods, or pouring sand between the ground and the walls.

Generally, when a modern technology is introduced, it may imply that it is a new concept, but careful investigation, in most cases, reveals that the technology may be new but application of its concept may go back to long before. It should be noted that the isolation concept was adapted and used in ancient times.

Application of base isolation on foundation systems are the most critical components to ensure a long life for most historical structures. Without a proper foundation system, these structures could not survive for many centuries. Due to their importance, some detailed explanations are given on how foundations were constructed in ancient times. However, the focus is made on application of isolation concept. Although there are several types of foundations that function as seismic resistant system but only one type that is called ‘orthostat’ stone layers is explained here and its formulation is presented in this paper.

2- THREE LAYER STONE SYSTEM

There are some structures in different countries whose foundations are very much similar to each other. The Ormetash obelisk in Istanbul is one of them. The Ormetash which is located in Sultan Ahmet Square in Istanbul is a pier constructed of dry dressed stone of 32 meters (Fig. 1). It was erected in 4th century AD and was repaired by Constantine and his son Romanos. The Ormetash Obelisk is placed on a marble base over three layers of orthostat stones. The diffraction of earthquake waves under the ground and coming up with inclined or vertical direction and hitting the ground surface has a complicated mechanism when arriving at orthostatic stones. These three layers of orthostat stones serve to absorb the earthquake waves, which are concentrated at the primary time causing less movement to be transferred to the superstructure. The surface waves of Love and Raleigh are mostly prevented by these 3-layerd orthostat stones. Some details and analytical investigation is explained in sections 3 and 4 to show that how this obelisk could survive for more than 17 centuries in the high seismic location of Istanbul that was hit by about 80 medium to strong earthquakes during this period.

So many examples, especially tall column structures, can be seen in different locations in the world. One can realize that the 3-layered stones under their foundation were the reason to make them withstand against earthquakes, although many centuries have passed. Some familiar places can be seen in Greece as well (Fig. 2).

It was tried to prove such analytical solution by computer analysis but no computer program can do such analysis for a complete solution at the moment. The reasons are explained following a detail consideration of such engineering mechanism for the finite element analysis. However, importance of such type of foundation is emphasized because it has been the key for earthquake protection of structures for at least 4 millenniums. The seismic isolation system had been forgotten until a few decades ago. It was again introduced with modern technology around 25 years ego. At present, less than 10,000 structures in the world have utilized modern base isolation system which comparing to the total number of structures in the world is very low.

The main idea at the present time is to anchor the foundation perfectly to the ground that causes the structures to shake together with ground during an earthquake. It can easily be seen that in the ancient times they tried not to anchor the structures to the foundation but they did the reverse. This could be acquired by putting the base of walls or columns on the foundation by no mortar between the stone layers. Next section goes further to more ancient times and finds how this system was developed and adopted for several millenniums.

Figure 1. Ormetash Obelisk with its orthostat stones that goes back to 17 centuries ago.

Figure 2. The columns of Parthenon and Erechtheion in Greece that are still standing after many centuries.

3- THE ORIGIN OF ORTHOSTAT FOUNDATION SYSTEM

The Tomb of Cyrus in Pasargadae, southwest of Iran which was built in 550 BC is likely the oldest structure that is known to have an orthostat foundation (Fig.3). The orthostat foundation is the key information of this research which is referred to it in the Bible as follows:

Ezra 6 of the Bible reads "… **3** In the first year of King Cyrus, Cyrus the king issued a decree: '*Concerning* the house of God at Jerusalem, let the temple, the place where sacrifices are offered, be rebuilt and let its foundations be retained, its height being 60 cubits [about 27 meters] and its width 60 cubits; **4** with three layers of huge stones and one layer of timbers.

And let the cost be paid from the royal treasury... **14** ... And they finished building according to the command of the God … and the decree of Cyrus, Darius, and Artaxerxes [Ardeshir] king of Persia. **15** This temple was completed on the third day of the month Adar; it was the sixth year of the reign of King Darius…"

One of the main functions of foundation is its ability to resist earthquake forces. In earthquake prone areas of Anatolia, for tall columns or walls, even on rock, some flat small stones like pillow were laid to absorb the first shock of earthquake forces on the pre-prepared soil over foundations. The number of layers in most of the times was three and no mortar was used. Then, some big foundation stone layers were put over these small stones where normal construction of the walls was built. During earthquakes, a small slip occurs by the movement of these small stones. It is interesting to note that in the areas where the seismicity is low or with no earthquake, such type of foundations are not generally present. However, since the technique had already been introduced in those ages, the method was adapted in other areas as well. These large foundation stones are called 'Orthostat' stones. For better function of such foundation, the surroundings of the orthostat stones were left empty. They also prevent moisture penetration into the structure.

Figure 3. King Cyrus Tomb in Pasargadae (southwest of Iran) built in 550 BC. On the right, a close view of the smoothed cut-stone layers with no mortar between them can be seen.

Even though the stones are over each other without any mortar or sticky material, the mechanism is in such a manner that actually no sliding occur; or better say, they may slide a little but they come back to their original position following the earthquake. The fact is that we observe the structures still standing after over 2500 years without any movement of stones. If they had moved just a little, say less than even 1 cm in each strong earthquake, then, they should have moved tenth of centimeters during this long period. Some analytical investigations are being performed to verify why the stones remain standing in their original places. One of the reasons may be the upward component of earthquakes which has not been seriously taken into consideration up to now.

4. SOIL-FOUNDATION-STRUCTURE INTERACTION IN SEISMIC ENVIRONMENT

Earthquake motion propagates in soil layers by diffraction and refraction and come to the surface with horizontal and vertical components that are called P and S waves. P wave compresses and loosens the environment volumetrically and as it spreads inclines to vertical direction while passing through the layers of the earth. It approaches to the plumb (tends to be vertical) till reaching the surface. S waves are also known as drift waves. They form drift oscillations which run in perpendicular to the undulation direction. Amplitudes of P waves are small and of S waves are big that can cause destruction. The P waves emerge to the surface in plumb line that causes vertical motions in the surface while S wave causes horizontal motion. As the ground is very complex with many rock layers, it may not be possible that the p waves come to the surface completely vertical. By installing some foundation layers without sticky materials this can be acquired.

Due to the boundary conditions, amplitudes of the earthquake wave doubles in free surface as a result of acceleration of gravity accompanying with vertical P wave. It becomes $\{g+2a.\sin(\omega t)\}$ in the structure on the surface of the ground by oscillations with 2a accelerations due to earthquake:

$$W(t)=m.\{g+2a.\sin(\omega t)\}=m.g+2a.m.\sin(\omega t) \qquad (4\text{-}1)$$

The weight of the structure on the surface, W goes through the harmonic change dependent on time. The effect of (mg) which is the modulus of the vertical load is accompanied by harmonic 2am.sin (ωt) load. Vertical load vector remains with the same sign in each period and it changes its direction in the event of rare case of (a) value (Fig. 4a).

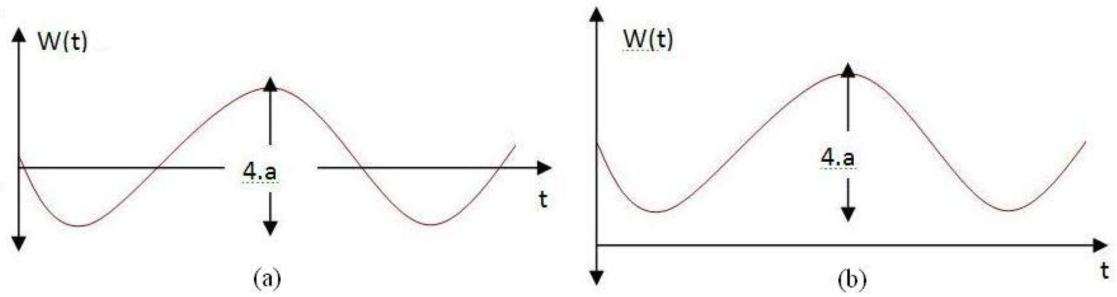

Figure 4. a) Weight of a structure during an earthquake with acceleration a, and b) Changing signs of acceleration in drift motion of the ground.

S wave always repeats the full harmonic 2a.sin(ωt) motion. Load vector which constitutes drift tensions turns to one (+) and one (-) vector by changing sign in each period (Fig. 4b).

It is easily seen that the acceleration of gravity's up and down in the layer from where the P wave emerges to the surface. Drift stresses which are formed by the weight of the structure up and downs in every period of the earthquake in horizontal planes. The drift stresses that up and downs in the structural horizontal planes can be used to reduce the effect of S wave energy. It can be said that S wave with the horizontal oscillation doesn't convey very much to the structure when vertical acceleration value is at maximum. At the same time when vertical acceleration is minimum, the drift tensions decrease to an important proportion in the horizontal layer. This shows that the coefficient of friction in the vibrant surface decreases with the vertical vibration period and amplitude of the plane. The mathematical formulation for finding transition parameters can be derived for structure with dilated foundation in period interval. We can make the function of the two motions that will be formed the base for the calculation by eliminating the time in the W(t)=m.{g+2a.sin(ωt)} function to a period interval (Fig. 5).

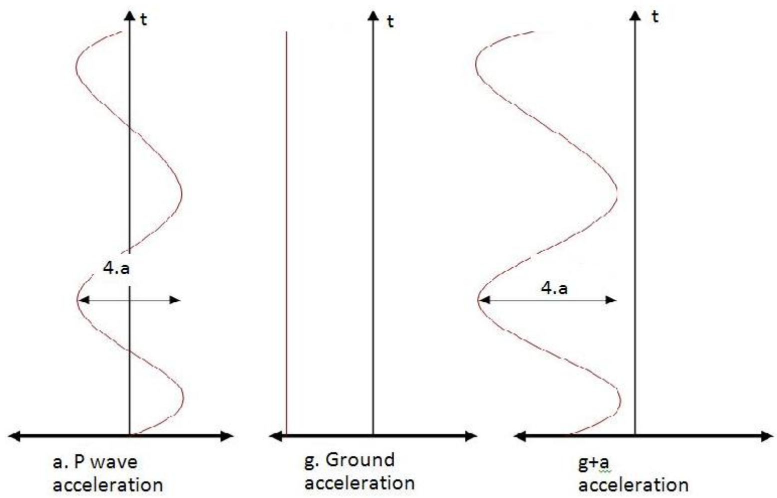

Figure 5. Increasing and decreasing of acceleration on the ground surface due to earthquake.

Some assumption can be made to continue the calculation with the value of the vertical loads W=m.{g±2a) in the structure. We accept the vertical acceleration of gravity as positive (Fig. 6).

In Fig. 6, a is the acceleration of the P wave, m is the mass of the structure, A is the S wave acceleration on the ground and μ is the coefficient of friction of the horizontal plane made between the foundation and block. $N = \frac{a}{A}$ = P is the proportion of the P wave acceleration to the S wave acceleration. This value is in the position of $N = \frac{2}{3}$.

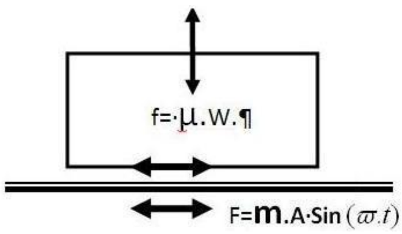

Figure 6. Vertical and horizontal motion of ground surface together with structure during an earthquake.

The force that the S wave can form in the horizontal direction on the structure's ground is as much as F=m.A Sin(ωt). It becomes F=m.A, if we degrade it to the half period interval. This force passes to the structure as it is and shakes it in the horizontal direction, if there is no drift on the ground. W=m.(g+2a) vertical load originates in the structure base in the (g+2a) state of P wave acceleration. The weight of the structure is W=m.(g-2a) in the (g-2a) state. If the structure is separated from the upper structure with dilatation on the plane from where it emerges to the surface if static friction force is f= μ.m.(g±2a). The shifting force magnitude which the earthquake will form in the horizontal direction is as much as F=m.A under the dilatation plane in the structure. The drift is formed if the friction force F in the dilatation is equal to or smaller than the shifting force magnitude.

$$\mu.m.(g \pm 2g) \leq m.A \rightarrow \qquad \mu = \frac{A}{(g \pm 2a)} \qquad N = \frac{a}{A} \rightarrow\rightarrow a = N.A$$

If we take it as $A = \alpha.g$; $\alpha. \Rightarrow$ is the earthquake acceleration parameter according to the acceleration of gravity.

$$\mu \leq \frac{A}{g \pm 2.N.A} = \frac{\alpha}{1 \pm 2N.\alpha}$$

$\mu \leq \frac{\alpha}{1 \pm 2N.\alpha}$ Two separate equations are formed in a period interval.

We can make the graphic of the change of the coefficient of friction with the earthquake acceleration parameter and make interpretations (Fig. 7).

We can determine the limits of the coefficient of friction for the formation of drift in the structure's foundations according to the change of the ground acceleration parameter of the earthquake. In the graphic, there is asymptote of the coefficient of friction in $\alpha = \frac{1}{2N}$ value for the $\mu \leq \frac{\alpha}{1 - 2N.\alpha}$ case. In the upper accelerations of the α value, the structure and stratum are separated. The vertical earthquake acceleration is bigger than the acceleration of gravity and between the structure and foundation is widened.

There is asymptote of $\mu \leq \frac{\alpha}{1 + 2N.\alpha}$ equality for the coefficient of friction $\mu = \frac{1}{2N}$ value. Coefficients of friction above this value don't let the drift in the structure's foundation. For every value within these borders, drift occurs in the structure's foundation.

When N=$\frac{a}{A} \leq 1$ or N≥1, we evaluate $\frac{1}{2N}$. In the N≤ 1 environment, P wave of the earthquake is bigger than the S wave acceleration. It makes it easy that friction can occur in the structure's foundation for the high values of the coefficient of friction. When N≥1, it is necessary to form planes with low coefficient of friction for the formation of drift in the structure's ground as the P wave acceleration is big.

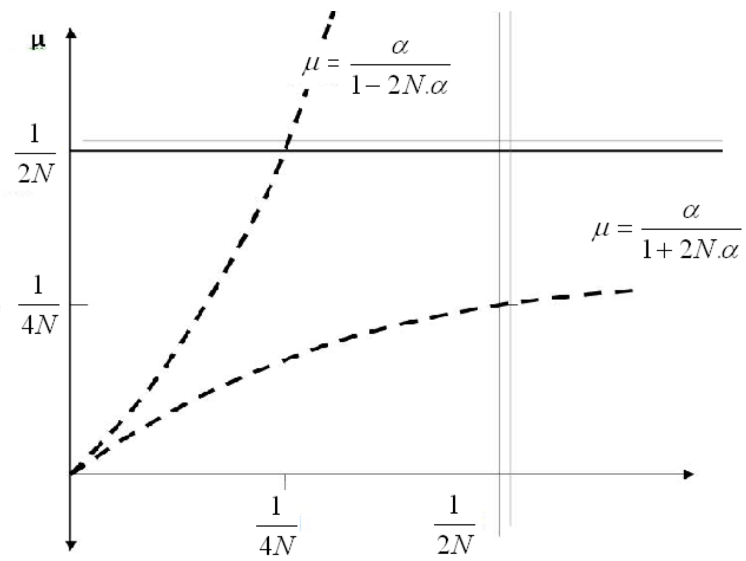

Figure 7. Diagram showing the structure's motion depending on the acceleration ratio to that of the coefficient of friction

The calculations are about the static coefficient of friction. In addition to this, there is also kinetic coefficient of friction. The kinetic coefficient of friction is bigger than the static coefficient of friction. If the calculations are made according to the static coefficient of friction, it will be a safer region than the kinetic one. The drift of the foundation to the structure's ground causes important discharges in the earthquake energy which will pass to the structure. The energy caught in the earthquake waves loses strength with instant discharges is important for its effects on the structure. In this case the structure's foundation continues its oscillations without shaking. If the structure is anchored to the foundation the rest of the structure becomes the last layer that means above the foundation up to the roof. In this case the acceleration in the structure becomes doubled.

We can protect the structure from the S wave by using the fact that P waves reach to the structure first and form vibrations in vertical direction. That is to say that we can separate the upper block from the foundation by making dilatation on the ground surface. Vertical vibrations that the P waves form in the structure decrease the coefficient of friction in the horizontal dilatation on the foundation. S waves of the earthquake which reach to the structure's ground later are like reaching the free layer and discharge its energy thus cause horizontal vibrations not to reach the upper structure which then it stops S waves horizontal and destructive effects

We may examine the effects formed in the structure's columns and the W=m.(g±2a) function of two motions which are formed by degrading the time in the W(t)=m.{g+2a.sin(ωt)} function to a period interval. We can make the upper and lower heads of the columns' hinge forms to see the effects of the earthquake energy in the structure. By looking at the effects which P and S waves form in the structure, we can admit that the jointing of the column load is gathered in point A and floor reaction force is formed in point B. If we ignore the weight of the column in the height h, the reactive power will be as much as W.

We are thinking of the structure foundation translation of the column load in the position where it comes to point A as the critical condition. S waves which are one of the two effects of the earthquake make the columns in this position. Meanwhile we are profiting from the S wave energy of the earthquake. We do not consume energy for making the column loads to this position. We calculate the vertical effects of the P waves which are prominent in the structure when the loads are in this position (Fig. 8).

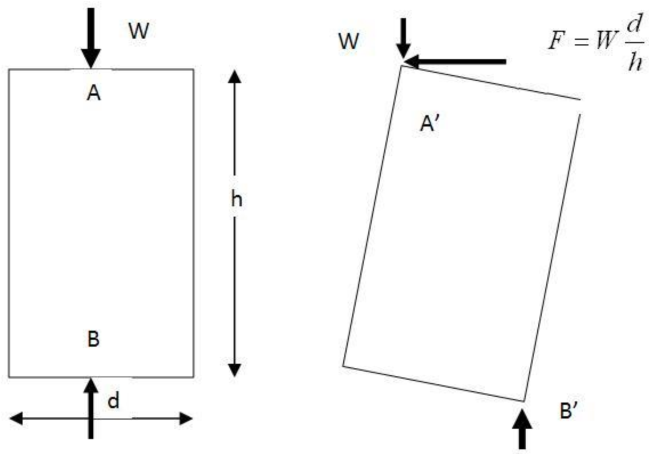

Figure 8. Parameters of motion of columns in the structure when dilated from ground

In Fig. 8, d is the width of column, h is the hinge interval which will be constituted in the column, W=m.g is the Column vertical load, m is the mass of the structure on the column, g is the acceleration of gravity, a is the P wave acceleration and A is the S wave acceleration. Here 'A' is greater than 'a'.

Earthquake shakes the structure with 'a' acceleration. The replacement amplitudes formed on the surface of the ground are doubled. These are velocity, acceleration and vibrations. The structures take the vertical motion energy from the P wave of the earthquake. This energy which results continuous loadings produce periodic effects on the columns. W load fixed in the column turns to the unstable load in W(t)=m.{g+2a.sin(ωt)} value. The formation of these effects is a result of earthquake energy.

While the W(t)=m.{g+2a.sin(ωt)} effect of the P wave on the structure is the constituting effects which decrease and increase, S wave constitutes a stable shear force which changes direction. While the direction change of S wave happens in an instant, effects of the P wave constitute the effects which increase and decrease without a direction change. 2a acceleration can be larger than g acceleration in earthquakes which occur rarely.

Column load forms *W*=m.(g+2a) load effect in 'A' position and horizontal force in $F = W\frac{d}{h}$ magnitude. This force is a vectorial magnitude which is repeated by changing sign. The sign of this force vector which is formed in horizontal direction changes direction with the effect of S wave. F force is a force vector which produces effect in the opposite direction for the shear force of S wave. Its effect increases and decreases with effect of harmonic motions of the vertical weight and changes direction dependant on S wave. It makes the columns which are separated from the plumb line with the effect of S wave return to the previous condition. If the necessary structural changes are made on the columns, we can benefit from the vertical load energy of the earthquake.

The proof of decreasing of the coefficient of friction with increasing of vibration is done by Assaduzzaman, et. al. (2007). This concept is unknown to our contemporary civil engineers as it is the main idea of preventing earthquake shock to enter the structure. In the literatures, only two types of frictions are explained as static and dynamic. The dynamic friction is always smaller then static. The main concept is that when the surface itself vibrates, the coefficient of friction decreases again to a significant amount and may become far less than dynamic. This means that during the earthquake motion due to simultaneous vertical and horizontal motion of the ground surface the friction between stones decreases. Thus, due to this vibration together with bouncing, the friction decreases and causes the stones to slide rapidly. We need a comprehensive computer program to adopt friction to be changed as the motion's amplitude and frequency change. This is the difficulty that we have encountered at present and should reach for a solution in the future investigation.

5. CONCLUSIONS

Paying a closer attention to the structures that are remained in earthquake prone areas with long history of civilizations, one can find clear evidences of layered stones (orthostat foundation) between the ground/foundations and the main structures. Analytical investigations show that the seismic resistant method used in the past was in such a manner that the earthquake forces were prevented from entering to the structure. Another word, a seismic base isolation concept had been adapted in order to make such mechanism work.

This paper explained some details of the analytical procedure to prove why layered cut stones have prevented seismic waves to enter the structures in ancient structures. More investigation on the analytical aspect of this method can offer the details on how this method can be applied in modern earthquake resistant construction technology.

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