16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4934

Registration Code: S-W1463139394

BASE ISOLATION FROM A HISTORICAL PERSPECTIVE

B. Carpani[(1)]

[(1)] *Researcher, ENEA – Seismic Engineering and Natural Risk Prevention Laboratory, Italy, bruno.carpani@enea.it*

Abstract

For the development of better design approaches to protect buildings from earthquake damage, base isolation, to reduce the seismic energy impacting on the structure, has represented a change of paradigm since it came to the fore in the second half of the last century. This paper presents a historical overview of base isolation to trace the principal stages of its scientific and technological development. It will show that, although presented as an innovative technique, the basic concept behind base isolation is far from being a modern development. In particular, the paper describes when and under what circumstances the basic principles of base isolation were for the first time conceived, tested and put in practice. One aim is also to give due credit to the actual inventor of the first base isolation device. Starting from that crucial event, the study follows a twofold perspective: on the one hand, it examines in chronological order the main stages of development, as well as the process of innovation by which base isolation has become a mature discipline, and on the other, it looks at the historical sources and the archaeological record searching for potential precursors. The data analysis shows that the idea of loosening the tie between the ground and the structure has its roots in antiquity, as evidenced by a set of construction practices like the interposition of sand or clay layers under the foundations. Although these technical solutions fit well with the basic principles of base isolation, this does not mean, however, that ancient builders had a real understanding of the potential anti-seismic effectiveness of their techniques.

Keywords: anti-seismic construction history, base isolation, ancient building techniques

1. Introduction

For the development of better design methods and protection technologies to mitigate the earthquake effects on structures, base isolation has represented a new approach in the field of seismic engineering, especially in the last two decades of the twentieth century.

Although defined as a modern or innovative technology, the basic concept behind base isolation is far from being a recent development. In fact, the idea of decoupling the motion between foundations and superstructure was thought of and implemented about 150 years ago, when earthquake engineering - or, more exactly, "the application of civil engineering to the problem of earthquakes" [1] - was at a very early stage of its development. Moreover, as the study of ancient foundations techniques attests, the practice of loosening the joint between ground and structure has a long history spanning more than three millennia [2]. Nevertheless, the innovation process from invention up to the stage of mature discipline shows that base isolation was resisted for a long time, gaining widespread acceptance only in the second half of the twentieth century.

The invention of the first device designed on the basis of the base isolation principle, explicitly intended to reduce the seismic energy impacting on the structure, was actually published as early as 1868, marking a watershed in the history of this technology: it opened the way to the future development of the discipline, but on the other hand it raises some questions about the existence of precursors, and to what extent this achievement was due to the body of technical knowledge of the time.

Starting from a close examination of that crucial but little-known event, the purpose of this work is to trace the development of base isolation in two ways: looking forward towards the stages of the innovation process that has led to the present-day advanced technology, and looking back to investigate the precursors of base isolation in the historical and archaeological records.

2. The invention of the first base isolation device: David Stevenson's "Aseismatic Joint"

Priority in the development of the base isolation principle belongs to the Scottish engineer David Stevenson. In March 1868, he presented a paper entitled *"*Notice of Aseismatic Arrangements, adapted to Structures in Countries subject to Earthquake Shocks*"* to the Royal Scottish Society of Arts, which published it the same year in their Transactions [3]. Stevenson was an advisor to the firm entrusted by the British Government with the task of erecting a series of lighthouses in Japan, which had opened some of his ports to free trade. Considering the high seismicity of Japan, one of the major problems was to ensure the stability of the lamp apparatus to avoid any interruption of the light signal. Stevenson was acquainted with the outstanding report of Robert Mallet on the 1857 Great Neapolitan Earthquake [4], and particularly with the sections describing the way in which buildings behaved under seismic waves. After describing the circumstances that led him to take into consideration the effect of earthquakes, he observed that:

"It is evident that any sudden lateral motion of the earth, on which the building rests, must be communicated to the foundation of the structure, and thence through all the rigid and unyielding materials of which it is composed to its very summit, where the violence of the shock will be aggravated by the greater elevation of the highest point of the building above the source of motion. On fully considering this action of earthquakes, it occurred to me that what was required to neutralize their shocks was a *break* in the continuity of the rigid parts forming the structure, so as to prevent the propagation of the shock, with increasing violence from its foundation, to its summit. The idea being that, in some horizontal plane, the building should be cut through and separated, so that the sudden motion of the lower portion should not be directly communicated to the superincumbent building." (the italics are Stevenson's) [3].

Here, in all probability for the first time, is set out the basic principle of base isolation.

To prevent the overturning of the lamp table carrying the fragile lighting equipment, Stevenson designed a rolling-bearing device, which he called *aseismatic joint,* consisting of bell-metal (a sort of bronze) balls set between cups hollowed out of two plates of the same material (Figs. 1-2). He was aware that the action of the device would be due to the inertia of the superstructure, and that "*theoretically* the greater the weight of the superincumbent mass the more perfect will the action be". He then proceeds to explain how the joint works when applied to the base of a building: after the seismic shock, "The earth,…, would move in some direction, carrying with it the foundations; but, in consequence of the break in continuity caused by the intervention of the balls, and the inertia of the superincumbent mass, the whole effect of the shock, if it was not an excessive one, would be to move the foundations below the superstructure, causing a slight corresponding motion of the balls in their cups; and, on the shock ceasing, the balls would instantly resume their places in centre of the cups." [3].

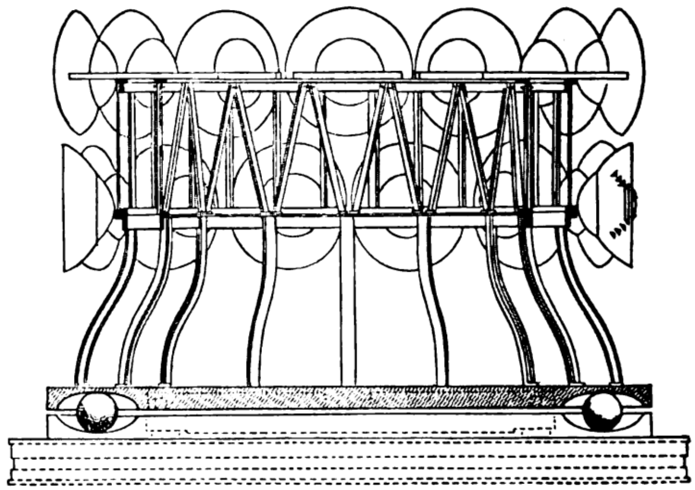

Fig. 1 – Section of the lamp table provided with the aseismatic joint [3]

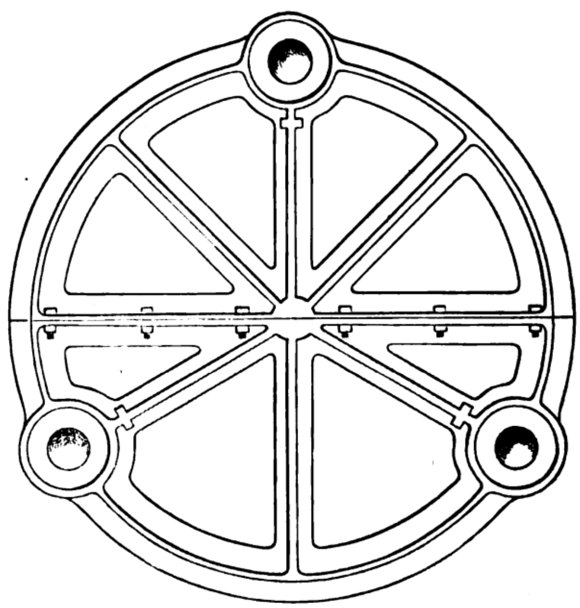

Fig. 2 – Plan of the lamp table [3]

It is interesting to note that one of the criteria adopted to determine the dimension (not reported in the paper) of the balls and cups system, as well as of the balls race shape, was to meet the maximum ground motion displacement measured by Mallet during his survey, which proved to be not more than 8-10 cm. For such an amount of motion, the device should have been able to restore the foundations-superstructure system to its original position.

With the aim of verifying the aseismic properties of the device, a full-scale model (about 2.50 m. in diameter) was built and experimental tests were carried out. The trials consisted in repeated series of blows struck with a heavy mass impacting the table in horizontal and oblique directions. According to Stevenson's account, the results were completely satisfactory, as the light apparatus remained unaffected even by the strongest impacts, whereas it was quickly overthrown when placed on the table without the isolating device.

The plan was approved by the UK Board of Trade, so that seven lighthouses provided with anti-seismic lamp tables were built in Japan from 1869 to 1872. Stevenson thought the device suitable also for larger scale applications to building structures; to that end he planned to make use of iron instead of bell-metal and to shape the plates on which to house balls in the form of a truncated cone. A few years later, two lighthouse iron towers provided at their base with the aseismic devices were built and sent to Japan, but the ship unfortunately sank during the crossing, thus missing the opportunity of predating by several decades the first seismic isolated building in the world.

The actual effectiveness of the *aseimatic joint* was a highly controversial question at the time. Stevenson had to meet what will become one of the basic requirements of base isolation: to limit excessive sensitivity of the device to ordinary disturbance such as wind or small earthquakes (in this case, the problem was table unsteadiness during maintenance operations on the light equipment), while allowing the device to acting freely during earthquakes. To increase the stiffness of the system, a vertical robust spring fixed to the lower table was inserted, joined to a ball working in a socket in the centre of the upper table (Fig. 3) [5].

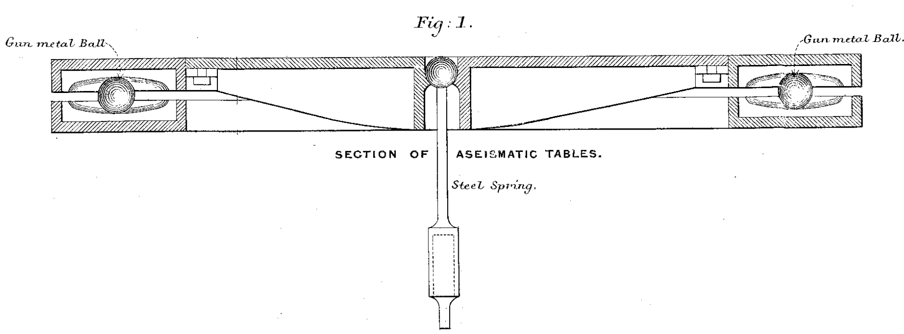

Fig. 3 - Particular of the aseismatic table improved with a vertical spring [5]

According to Richard H. Brunton, the Chief Engineer of the Japan lighthouses project from 1868 to1876, the improvement was only partially successful, but he did not give further details. As a matter of principle, Brunton refused to accept Stevenson's new approach and after the above-mentioned shipwreck, the rolling devices were no longer employed. However, the analysis of the data available shows that the *aseismatic joint* did not perform as badly as transpires from Brunton's accounts [5]. In fact, considering the seismic effects on the lamp apparatus, of the seven lighthouses provided with sliding tables three were not affected, while two suffered serious damage. One of these was the Tsurugisaki lighthouse where the arrangement was upset and all the lamp-glasses thrown down by an earthquake in March 1882. However, the tables had been previously clamped to prevent any motion during the adjusting operations, and for some reason they had not been freed from their fasteners. Two years later a severe shock struck the same lighthouse, this time with the table in working order, damaging the lamp apparatus once again; according to the light-keeper report, many lamp-glasses were broken, but the working of the light was interrupted for only five minutes [6]. So, it seems that the main drawback of the anti-seismic system lay more in the difficulty of handling the routine operations properly, than its capacity to mitigate earthquake effects.

As regards the issue concerning the strategies for reducing seismic risk, it is interesting to note that even the principle followed by Stevenson was an innovative one, since, to a certain extent it resembles the limit state design method. Adopting a similar approach, he defined the objective as the fully operational state of the lamp, and its associated performance criteria as not to exceed the maximum estimated displacement. Realizing that a complete protection of a mechanical device from earthquakes occurring at very long intervals was not practicable, the performance objective was to expect the mitigation of effects against all earthquakes and adequate protection against "the most of the ordinary shocks", in other words, no damage from frequent earthquakes and mitigation of the major ones.

To conclude this section, what prompted Stevenson to adopt an approach based on the control of the impacting energy rather than the increase of structural strength and stiffness is worth pointing out. In the documentation he received from Japan, there were several Japanese volumes on wooden architecture describing how the traditional Japanese building did not have fixed foundations, but rested on vertical posts rounded at the bottom and standing on foundation stones; as a result "a joint is thus formed, the continuity of the structure is broken, and by this arrangement the Japanese have made an approach to what I proposed to do more perfectly by the balls and cups". Furthermore, he understood the dissipative properties of the flexible joints system connecting the timber frame structure, made without nails or bolts by means of "dovetailing and wedging, which admits of adjustment after being disturbed by the wrench of an earthquake shock" [3].

3. Further developments 1870-1909

For some reason, Stevenson did not patent his invention, so that, two years after the appearing of the *aseismatic joint*, a long sequence of patents based on the identical ball bearing system appeared. The first to obtain a patent on an earthquake-resistant ball system was a certain Jules Touaillon of San Francisco in February 1870 (Fig. 4). The striking resemblance to Stevenson's device is self-evident. Even so, in a great number of scientific papers and books Touaillon is wrongly accredited with having first introduced the concept of base isolation (a honour he shares with the English doctor J.A. Calantarients, as it will be seen below).

An important stage was marked by another San Francisco resident, A. F. Cooper, who in March 1870, only two weeks after Touaillon (and like him, possibly an amateur: a few years later he patented a medicated pad for treating rheumatism), patented a system which involved for the first time the use of natural-rubber bearings with the idea of dampening the shock and providing the building with an elastic cushion or a system of springs (Fig. 5).

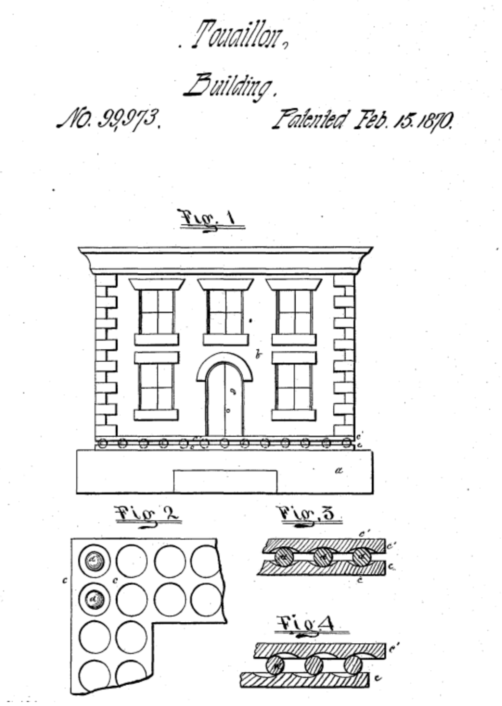

Fig. 4 – Touaillon's patent

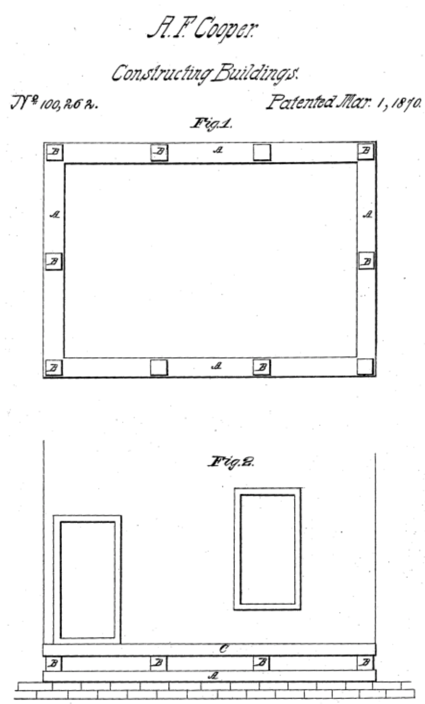

Fig. 5 – Cooper's patent

Tracing the development of base isolation, a special mention must be made of John Milne, the "Father of Modern Seismology". During his long residence in Japan (1875-1895) he was Professor of Mining and Geology at the University of Tokyo, where he carried out fundamental research for the progress of seismological science.

The amount of his work is truly impressive [7], and even just a concise summary of his scientific interests and achievements would be beyond the scope of this paper. Being both an engineer and a geologist, Milne also dealt with the problem of earthquake-proof building. Having had the opportunity to observe at first hand the effects on buildings of many earthquakes, he noticed that the European type of house, built of brick with firm foundations, suffered much more damage than the Japanese type, with a light and flexible wooden structure resting loosely on foundation stones. So to test the behavior of free foundations, in 1884 he built for experimental purposes a small (14ft by 20ft) timber building resting on four cast-iron balls. The balls were constrained by two "cast-iron plates with saucer-like edges" fixed between the foundation posts and the building. The building was instrumented and monitored showing good performance in mitigating seismic motion but very low rigidity under service loads such as wind. In an attempt to find a solution, the ball diameter was gradually reduced from the initial 10 inches to 1 inch, without satisfactory results. Finally, to increase the rolling friction, each ball was replaced with a handful of spherical grains (¼ inch) of cast-iron sand resting between two flat plates. According to Milne, in such a way the building became stable to wind loads, while the accelerations measured on the floor were about six times lower than those measured on the ground outside the house [8, 9].

Even though Milne did not publish any drawing, it is quite evident that his device is nothing but a variation of Stevenson's *aseismatic joint*. Milne never quoted Stevenson in his reports, and when Stevenson's son, David A. Stevenson, accused him of claiming the authorship of the ball and cup system, he replied he was not aware of Stevenson's paper and in his opinion the aseismic joint had been independently invented many times; but in the course of a lively controversy published in Nature from July 1885 to July 1886 [10,11,12,13], Milne failed to prove his point that Stevenson was not the first to conceive of base isolation.

Remaining in Japan, 1891 saw the first Japanese paper dealing with base isolation. It was published by Kozo Kawai in the Journal of the Architectural Institute of Japan [14]. The paper, entitled "Structures free from the maximum vibrations during earthquake", describes a small building equipped with precision instruments very sensitive to vibrations. The structure shows some peculiar features, such as a triangular shape to increase stiffness and a sort of rolling foundation consisting of a concrete platform resting on several layers of logs assembled in a criss-cross pattern. Moreover, in order to cut off the surface waves, the design includes a deep trench all around the building (Fig. 6).

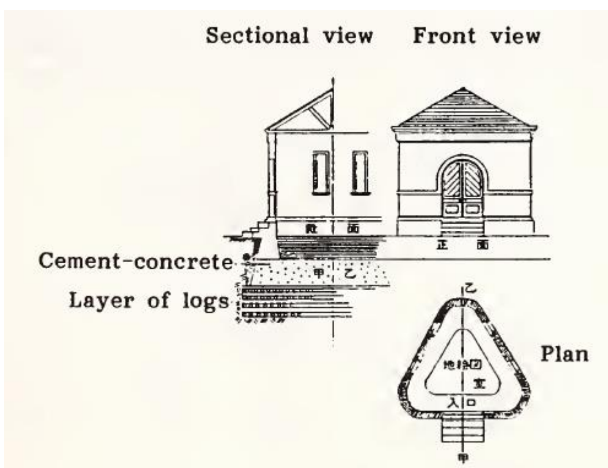

Fig. 6 – Kozo Kawai's anti-seismic building [14]

It is interesting to note that Kawai's main purpose was to avoid any damage to the contents of the building rather than merely design an anti-seismic structure. However, Kawai's proposal was not implemented.

The first decade of the twentieth century was marked by a series of disastrous major earthquakes which provided a renewed impulse to the research of new methods for mitigating seismic damage. The months following the earthquakes at Valparaiso and San Francisco in 1906 and Messina-Reggio Calabria in 1908 witnessed an increase in the number of patents based on base isolation approaches, particularly ball systems, but the most of them merely reproduced Stevenson's original idea (Fig.7).

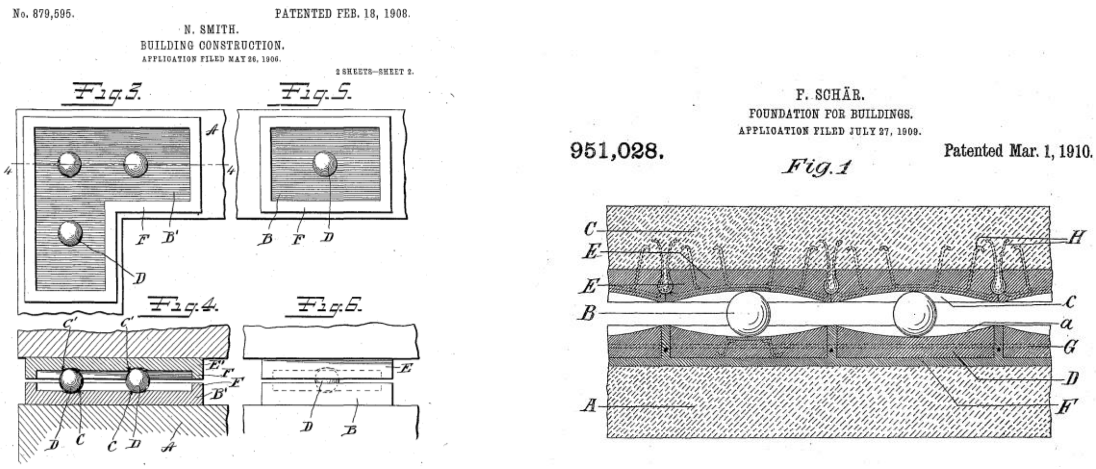

Fig. 7 – Two examples of ball bearings devices patented in 1908 and 1910

The most celebrated contribution to the development of base isolation was given by the English doctor J.A. Calantarients, who applied for a US patent in 1909. His construction method based on sliding foundations is well known, having been cited in dozens of papers and books. In brief, he proposed to build the superstructure on a "free joint", i.e. a layer of talc, fine sand or mica in order to create a lubricated surface on which the building can slide during earthquake motion. He also claimed that he had been the first to make experiments with balls "many years before it was done in Japan, or at any event before any amount of it appeared in the papers about 25 years ago."[15] As this paper has shown, Calantarients was wrong; he was unaware of Stevenson's work, and in all probability, he was referring to the above described experiments carried out by John Milne. Moreover, even the idea of interposing a layer of sand between foundations and superstructure may not be an original one. It was taken into consideration, for the first time by a national government, as a seismic-resistant method in the report of a commission of the Italian Ministry of Public Works as early as 1906 [16]. After the great Messina-Reggio Calabria earthquake of 1908, the Royal Commission appointed to make recommendations for the rebuilding, considered sliding base isolation as a possible alternative to the fixed-base design, but not technically advisable on large scale reconstruction [17].

4. Final steps towards a mature technology

From here, the successive steps of base isolation towards the status of the present-day mature technology are well documented. In Japan, at least two edifices of the Fudo Chokin Bank were built in 1934, using a foundation system patented by Ryuichi Oka, where columns with a hemispherical surface at the bottom rest on foundation plates (Fig.8) [14]. This "sway-type hinged column" system shows structural similarities not only with the traditional Japanese house, but also with the free-standing central column of the ancient multi-storied Japanese pagodas (Fig.9) [18].

Even though the two Japanese edifices were almost certainly the first modern isolated buildings, the most important contribution to the growth of base isolation depended to a great extent on the progress in natural rubber technology. In 1969, just a century after the Cooper patent, the Pestalozzi school at Skopje (MK) was the first structure isolated with unreinforced rubber bearings. This was an important step that led to the decisive improvement represented by the development and implementation of the multilayered laminated rubber bearings during the 1970s and 1980s.

To conclude this section, some considerations about one of the best known example of the early application of base isolation, which is also of special historical interest: the Imperial Hotel of Tokyo designed by Frank Lloyd Wright and completed in 1923, just in time to be struck by the 8.0 Mw great Tokyo earthquake. The structure performed well suffering only slight damage (grade 2 out of 5) but the first account of how it survived undamaged passed into legend (although recent damage assessments are less enthusiastic). The hotel was founded on alluvial mud and according to the great architect, “That mud seemed a good cushion to relieve the terrible shocks”, so a flexible, light structure was designed to float on the mud like "a battleship floats on salt water". Apart the controversy over the actual seismic behavior of the structure, the great vision in Wright’s imaginative conception cannot be denied: “Why fight the quake? Why not outwit it?” [19].

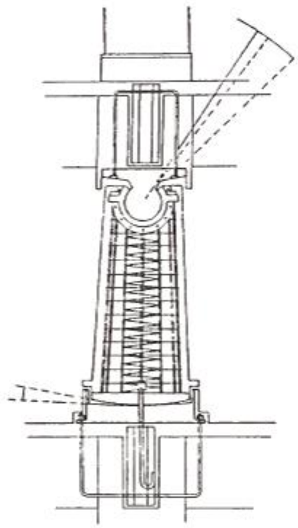

Fig. 8 – Ryuichi Oka hinged column [14]

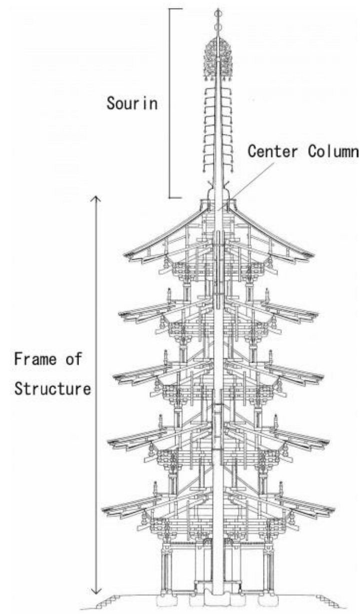

Fig. 9 - Section of Daigo-ji Pagoda, 8th c. AD [18]

5. Searching for precursors

Borges’ aphorism “Every writer creates his own precursors, because his work modifies our conception of the past, as it will modify the future.” may be pertinent also to the history of base isolation.

If based on a merely technical perspective, the analysis of ancient structures may fail to place historical and archaeological data in their relevant context, outside of which they may be open to misinterpretation. The study of ancient building techniques shows many examples of structures revealing foundations practices which fit well with the basic principles of base isolation [2]. This does not mean, obviously, that ancient builders had a real understanding of the potential anti-seismic effectiveness of their techniques, but nevertheless, some constructive features remain very impressive. The number of the investigated structures is such that it is not possible to examine them all. What it follows will be a brief description of a few examples among the most relevant to the devices above discussed (for a more detailed account, see [2]).

In chronological order, the most recent precursor is the Italian architect Francesco Milizia, who published his treatise on architecture in 1781 [20]. In chapter IX, “On earthquake-resistant houses”, he recommends building a strongly connected timber structure, the height of which must not exceed the width, not fixed in the ground but resting free on a stone platform. During an earthquake, such a house could only tremble, never overturn, because, he concludes, “this house is a trunk”. Very possibly, this is the only written description of free foundations before the 1868 Stevenson report.

Regarding the logs foundation proposed by Kawai, the origin of a similar arrangement goes back more than three millennia. It can be found in the vernacular architecture of northern Iran (Fig.10) [21], among the reinforcing techniques used in Algiers after the 1716 earthquake (Fig.11) [22], and finally in the Bronze Age architecture in Anatolia, where dendrochronological analyses have shown that all logs were cut in 1774 BC [23] (Fig.12).

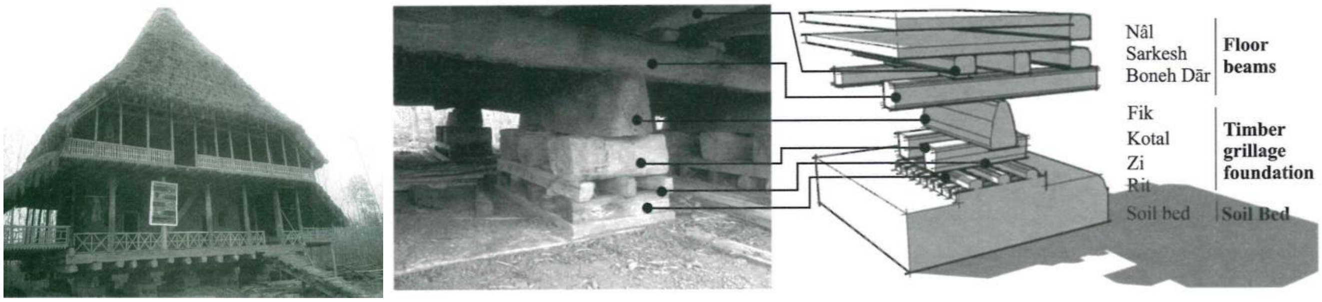

Fig. 10 – Timber grillage foundation in Gilān house, northern Iran [21]

Fig. 11 – Timber reinforcements after the 1716 Algiers earthquake (P. Clemente – ENEA)

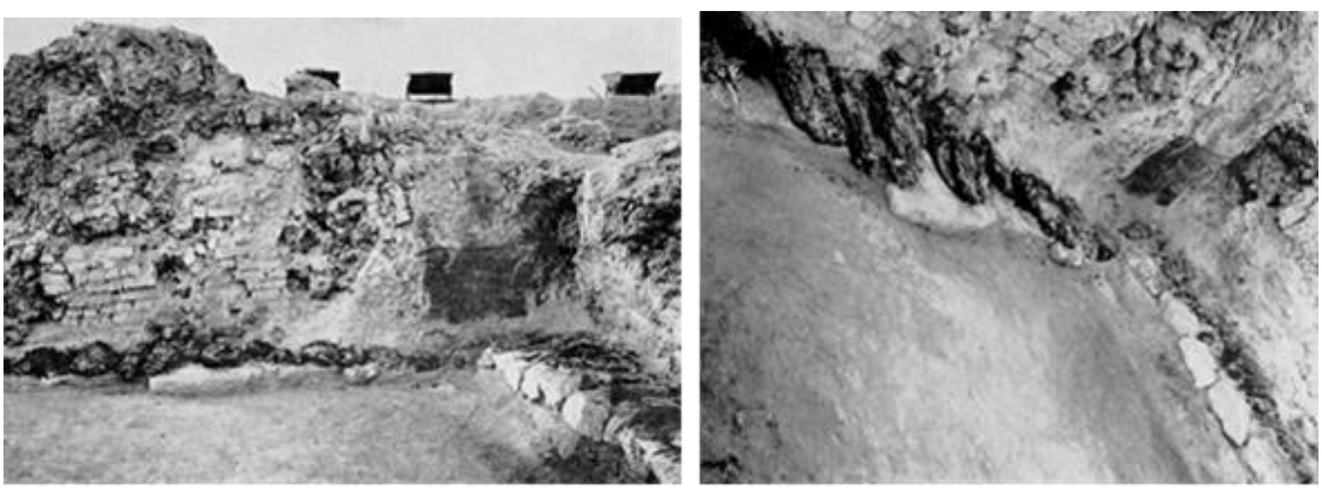

Fig. 12 – Acemhöyük Palace (Turkey): logs laid on stone slabs (the trees were all cut in 1774 BC) [23]

In ancient times, it was not uncommon for the ancient builders to interpose a sand, gravel or clay bedding between ground and foundations. Focusing on Greek foundation engineering, there are numerous examples showing some technical solutions used to face geotechnical problems. Among them, the colossal archaic temples in Asia Minor (6th BC): the Heraion at Samos, where the footings rest on trenches filled with clean sand [24] (Fig.13), and the Artemision at Ephesus, one of the Seven Wonders of the World. According to Pliny the Elder (*n.h.* 36,95), the temple was built on marshy ground to protect it from earthquakes (it is remarkable that Pliny's account is the only ancient source that makes reference to an antiseismic expedient). He also refers that to cope with such a bad soil conditions, layers of charcoal and wool fleece were laid under the foundations. Excavations have shown a huge foundation stone platform "floating" (using Wright's terminology) over a layer of clay mixed with charcoal [2, 25] (Fig.14). At Paestum, a layer of sand was laid between the bedrock and the massive stone foundations of the temple of Athena [26] (Fig.15). Another example is the temple of Athena at Ilion, founded on a sand bed 3.70 m high [27] (Fig.16). A different approach was used at Bassae, for the temple of Apollo, where a sort of mat foundation consisting in thick layers of limestone slabs and gravelly soil isolates the platform from the bedrock [28] (Fig.17). Finally, a very peculiar technique was found at Olbia, a Greek colony on the north shore of the Black Sea. By the early 4th c. BC, a new method for laying foundations was developed, consisting of layers of soaked and tamped loess, alternating with compacted ash and charcoal [29] (Fig.18).

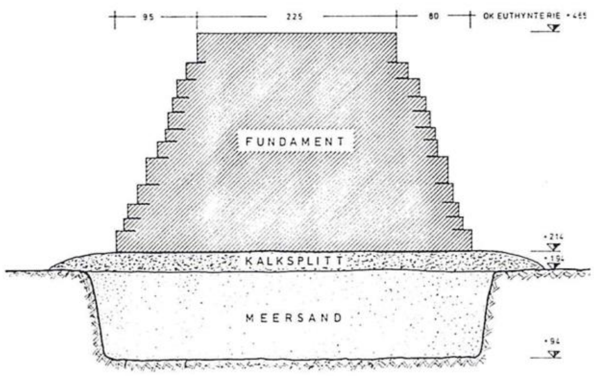

Fig. 13 – Heraion: foundations section [24]

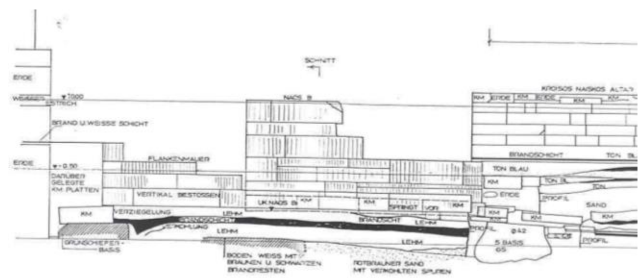

Fig. 14 – Artemision: section of the Cella foundations [25]

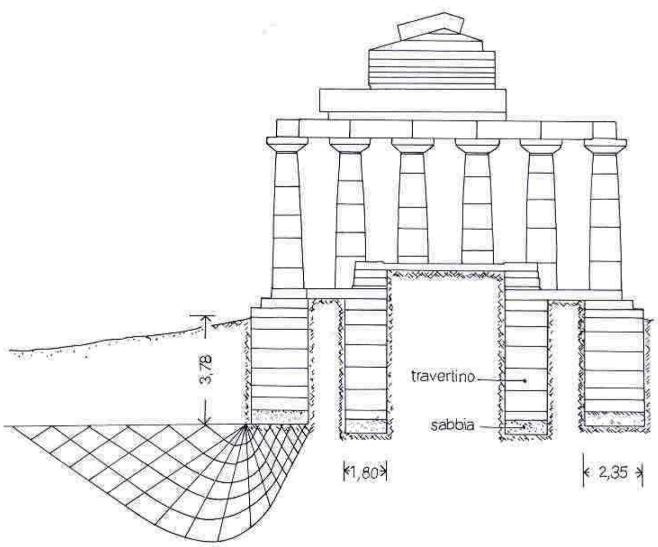

Fig.15–Athnaion of Paestum: sand bed under foundations [26]

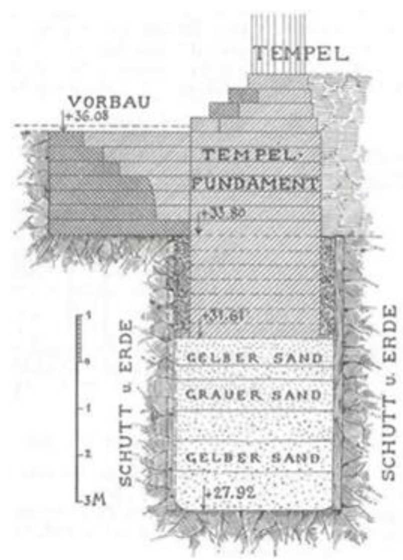

Fig. 16–Temple of Athena, Ilion [27]

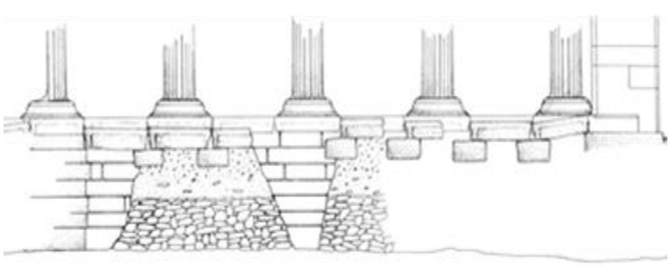

Fig.17 – Bassae: Section of the temple foundations [28]

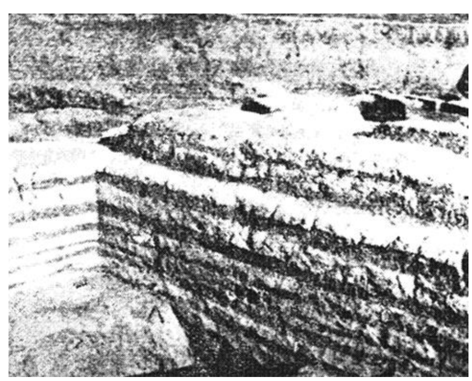

Fig.18 - Olbia: temple of Zeus foundations [29]

Finally, a mention of the only ancient written source concerning in some way vibration control. According to Diodorus of Sicily (*History* 18-27.3-4), the magnificent funeral carriage of Alexander the Great was provided with a sort of shock-absorber device, actually not well understood, formed by a pole "ingeniously fitted in the middle of the vaulted chamber so that by means of this device the chamber was able to remain unshaken by the jolts from the uneven places".

6. Conclusions

The analysis of the data presented here indicates that the first to conceive of, test, and implement a base isolation device was the Scottish engineer David Stevenson, who, in March 1868, presented his invention called *aseismatic joint* before the Royal Scottish Society of Arts. Starting from this point, the main stages of development of the discipline have been highlighted. Searching for the past achievements, our paper has also demonstrated that in antiquity the idea of loosening the tie between the ground and the structure was not unknown. Although these technical solutions fit well with the basic principles of base isolation, this does not mean, however, that ancient builders had a real understanding of the potential antiseismic effectiveness of their techniques.

Some concluding remarks about base isolation as innovative technology. Taking into account that Stevenson formulated correctly the basic principle of base isolation, it turns out that base isolation took more than a century to emerge as a mature technology. In this respect, it could be argued that its development has been rather slow. A practicable way to deal with this issue is to consider the development process from invention, i.e. the introduction of a completely new concept that makes a new construction or model possible, to innovation, i.e. the acceptance and widespread adoption of the invention itself, through the criteria of *accumulated knowledge, evident need, economic and technological possibility, and cultural social political acceptability* [30], where the first two are related to the stage of invention. Stevenson knew the innovative work of Mallet on earthquake phenomena, from which he took the data to calculate the size of the cups and balls system, and learned the flexible approach to structure from the Japanese traditional building techniques: this *accumulated knowledge*, in addition to the *evident need* of developing antiseismic methods in an earthquake-prone country, could have given an impulse to the invention process. Regarding technological possibilities, it has already been pointed out that the industrial development of multilayer rubber bearings marked a turning point in the innovation process. Cultural acceptability is a very complex issue, since innovations are often resisted for various reasons depending on economic, political and social factors. In Italy, for example, the lack of adequate legislation blocked the development of base isolation and other innovative anti-seismic techniques for several years.

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