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ANALYSIS OF SOLUTIONS TO REBUILD AQUILA CITY, ITALY, AFTER THE 2009 EARTHQUAKE

BY

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Abstract. The earthquake is an unpredictable natural catastrophe caused by tectonic plates friction. The present paper describes the results of studies related to the destructions and the consequences of April 6th, 2009, earthquake produced in the center of Italy, where a vast majority of buildings in Aquila city were ruined. Then, the paper continues with the measures of reconstruction and the seismic isolation solutions proposed and used in newly-erected constructions.

Key words: earthquake; friction pendulum isolators; project CASE.

1. History. Earthquake Parameters

On April the 6th, 2009, a devastating earthquake rocked central Italy, especially L’Aquila city; the earthquake had a magnitude of 6.3 degrees (Richter’s scale). Its epicenter was in the area of Paganica (Fig. 1) located in central Italy, at a depth of 9.5 km from the earth’s crust. This earthquake is considered as the worst recorded in Italy’s in past decade, although the Aquila is situated in a seismic zone where several earthquakes with a large magnitude were recorded in time. After the earthquake of April 6th, there were recorded

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about 280 aftershocks, some with a magnitude of 6.2 and the epicenter being located in the L'Aquila area to a depth up to 15 km.

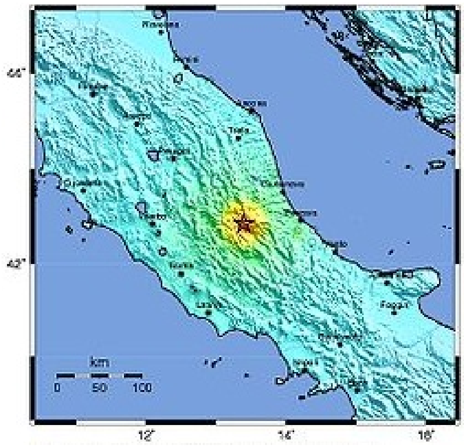


Fig. 1 – Epicenter of the earthquake of April 6, 2009.

2. Earthquake Effects

After the earthquake 23,000 people remained without a dwelling (Fig. 2), 1,500 people were injured, more than 180 people died and dozens were missing. The first concern of the authorities regarded rescuing people trapped under the buildings; then, there came the issue of finding solutions for the accommodation of people in distress in tent camps, schools, gyms. Obviously, the intention of adopting a temporary solution with relevant costs indicates the intention of the authorities to find a final solution type in the shortest time possible.

Fig. 2 – Earthquake effect.

Fig.3 – Formation of the plastic articulation in the pilots.

In 2001, in Aquila, there were 24% reinforced concrete buildings and 68% masonry, of which 55% were built after 1945. After the successive earthquakes that occurred in Italy, after the changes of the seismic rules, Aquila

City received an a_g = 0.261. All new buildings were built in the light of the amended rules, a fact that was reflected during the assessment of damage, when it was found that new buildings had less damage.

At the reinforced concrete buildings which did not comply with the regulations in force, it was noticed that most pilots had cracks in the upper part (Fig. 3); it is obvious that, if the new regulations had been observed, this could be avoided. During an earthquake, the pilots with considerable vertical force may form plastic articulations at the end, transforming the structure into a mechanism. As the plastification area was not correctly executed, the longitudinal reinforcements lost stability and bent down, another aspect which could be avoided if sufficient transverse reinforcement had been provided.

Another weakness in the reinforced concrete buildings is represented by the vertical irregularity (Fig. 5) as well as the flexible ground floor that can cause the destruction of the weak zones (weak floors collapse).

Fig. 4 – Masonry structure damage.

Fig. 5 – Flexible floor collapse.

The damage to the masonry structures are significant (Fig. 4). The types of failure in a masonry structure are of many kinds. A well-built masonry structure should behave as an entire structure. For this reason, in seismic areas, according to the new regulations, only confined masonry structures must be erected. Older buildings show high seismic risk as they are not confined.

3. Decisions to Rebuild

After restoring the living conditions of the distress victims the problem of long-term reconstruction of the city was taken into account. It was decided that construction work will be performed as quickly as possible, therefore it was opted for the typified and prefabricated members. The decision-makers opted for the project C.A.S.E., although this project was expensive; the rapidity of its construction proved to be the only solution. This project aimed at implementing the following principles: innovation, building capacity, Italian technology and transparency of financial operations. This project is one of the most expensive in recent decades, reaching a value of 630 million Euro,; however, the average daily production is only a hypothetical one. Mainly due to prefabrication reasons, the final choice was for friction pendulum seismic isolators as they formed the only system suitable for the design.

4. Constructive Solutions

In brief, the basic concept adopted consisted in building reinforced concrete piles with seismic isolators on the upper end over which the slab foundation of the building was to be laid. Piles are dimensioned without knowing the intensity of the earthquake, the building weight being distributed evenly across the upper slab due to higher stakes. The piles are to have a height of 6 m so that at the basement a parking to be arranged.

The foundation chosen was of slab-type to evenly distribute the load brought by the piles. The slab thickness was of 0.5 m, as required for breakdown reasons and load distribution of the future structure.

In structural design, special attention is paid to the execution time and costs. To reach such purposes, is necessary to standardize the production up to utmost, and this even tends towards the process of industrialization in construction.

The structural solution used for carrying out a seismic isolation system consisted of two rigid 0.5 thick concrete slabs reinforced in two directions, of dimension 21 × 57 m, among which 40 piles are placed; the seismic isolators are laid above. Piles are embedded at the bottom, with the help of anchors in the lower plate which acts as a slab type foundation. Above the upper plate one can freely construct and in this way the architecture of the structure shall be diversified.

Fig. 6 – Seismic isolators system.

The role of insulators is to achieve a vertical structure with high rigidity and high flexibility in the horizontal plane. Structures made in this way behave similarly with conventional buildings until the horizontal seismic forces exert their power and the seismic isolators intervene in the operation.

This solution of seismic isolators requires three elements (Fig. 6)

a) infrastructure, the foundation connected to ground;

b) the containment device, characterized by a large deformation in the horizontal plane and high vertical rigidity, and having the role of connecting infrastructure with superstructure;

c) the superstructure representing the structure base.

The advantages of this seismic isolation system are the followings:

a) the seismic isolation is made over all directions;

b) insulators are capable of energy dissipation;

c) the structure remains in the elastic area throughout the earthquake;

d) insulators are not destroyed, and hence there are no costly repairs after the earthquake.

The solution adopted is identical for all buildings, but due to a series of different parameters (such as soil type), the constructive technology elements (walls, piles, bridging) and construction materials vary (concrete structure, wood, steel, precast).

In the planning stage two seismic isolation systems were proposed: firstly, to use 12 elastomer isolators and 28 multidirectional sliding supports, and secondly, to use 40 sliding spherical bushings, friction pendulum isolators. Both systems are compatible with design requirements. The seismic energy dissipation capacity of the system with elastomeric isolators is approximately 12%, while the dissipation capacity of the friction pendulum isolators is approximately of 20%. The friction pendulum system ability to travel horizontally is only of 260 cm, while that of elastomeric isolators is of 300...360 cm.

During the tender and bidding stage it was allowed to propose any insulator solution, if the design data admitted it. During the tender stage, the only solution mentioned was based on the friction pendulum system as in the piles, there occur large axial forces which cannot be taken over by elastomeric isolators because they do not exhibit vertical stiffness.

The friction pendulum system was designed considering the relationship

$$F = M_g\mu + \left(\frac{M_g}{R}\right)d\ , \tag{1}$$

where: M_g is the gravitational force (axial); $m = 0.3$ – friction coefficient; $R =$ $= 4$ m – curvature radius of the spheres; d – design movement.

The effective stiffness of the designed buildings is

$$K_{\text{eff}} = 14,615 \text{ kN/m.} \tag{2}$$

The period of vibration of the isolation system is

$$T = 2\pi\sqrt{\frac{M}{K_{\text{eff}}}} = 3.29 \text{ s,} \tag{3}$$

and the amortization will be

$$\xi_{\text{FPS}} = \frac{2\mu M_g}{\pi K_{\text{eff}} d} = 20.1\%. \tag{4}$$

The plates mentioned were subjected to numerous tests and checks using the finite elements method, applied to many types of work loads and more combinations of piles arrangements; the selected one was that which gave a better resistance. Further tests were conducted for slab penetration, for the support solution, in hundreds of cases.

The piles were checked and the reinforced concrete piles were reinforced appropriately, but to shorten the building time, metal posts were favoured.

The following data need to be emphasized:

a) The entire structure is supported by a single structural element: the piles/drivers which have to take over more effects and more action combinations.

b) The problem of slab penetration must be avoided, by a proper distribution of vertical loads.

c) The maximum pile stress is 2,800 kN while in combination with earthquake.

d) In insulators, under no circumstance, tensile stresses may occur.

e) The own vibration period of the superstructure above the upper plate is less than 0.5 s.

f) The structural eccentricity between the weight centre and stiffness centre must be less than 5% of plate length (57 m) and below 10% of the transverse length (21 m).

g) The seismic building weight above the upper plate will be below 2,100 t, a value considered as representing the upper plate without its weight.

h) The superstructure was designed according to DM 14/01/2008 regulations and horizontal actions were calculated according to NTC 2008.

5. Manufacturing Technology

In the manufacturing technology one can distinguish five major phases: a) land-levelling operations; b) slab building; c) piles building; d) preparation and application of seismic devices; e) building the upper plates.

To finish in good time, the companies had to cooperate and synchronize theirs activities so that the continuity of the work could be ensured. The co-workers were

a) three companies that provide land levelling and preparing building sites for execution;

b) two suppliers of concrete-producing 5,000 m concrete/day;

c) one provider of reinforcements, producing 400 t/day;

d) two suppliers of steel piles with a capacity of 80 riders per day;

e) two manufacturers of seismic sinks, 80 pieces/day;

f) three companies that assembled all the materials (layout fittings, putting the carcasses, the upper plate and slab shuttering, concreting).

The superstructure was made with several kinds of materials (Fig. 7)

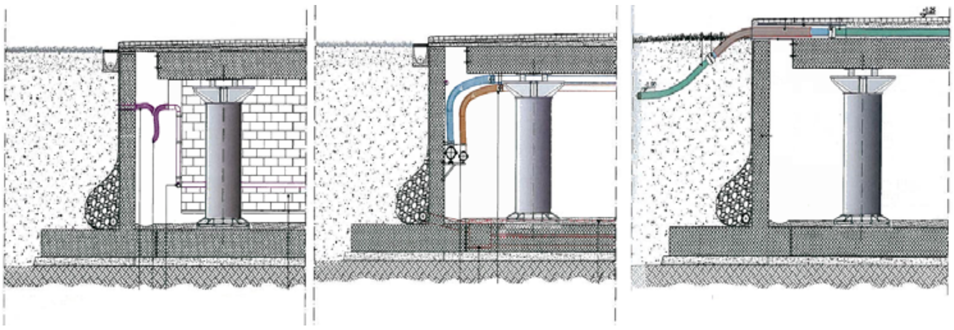
a) metal superstructure (used in about 20% of constructions, frames are bracing on each floor);

b) wood superstructure (used in about 50% of constructions) formed of three elements: supporting walls, platform frame type framed panels, frame beams and columns;

c) concrete superstructure (used in about 30% of cases) in approximately six types of structures. With this superstructure, one obtains the greatest reduction of manpower on site, because most parts are prefabricated.

a *b* *c*

Fig. 7 – Types of structures: *a* – metal superstructure; *b* – wood superstructure; *c* – concrete superstructure.



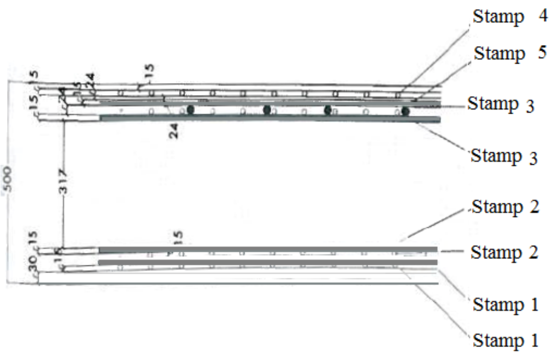
a *b* *c*

Fig. 8 – Installation: *a* – water; *b* – wastewater discharge; *c* – gas.

The above mentioned elements represents the structure of the building, to which there will be added the thermal insulation, sound insulation and utility installations. Power installations, water networks, heating, gas installations (Fig. 8) had to be so flexible as to allow the base movement without damaging the building systems.

Concrete was chosen according to the rules NT-2008 in force, of S5 class compacting concrete, which is compacted under its own weight without requiring additional compaction. This concrete was useful as it enters areas that are considered difficult to cast, such as the piles anchors.

The steel reinforcement used in the concrete slab and plate is B450C class. For simplifying execution and verification it was decided to use 10 typified elements (Fig. 9), combined in more ways to reinforce both the upper and lower reinforcement.



	Reinforcement
Stamp 1	Ø14 step 100 mm x 100 mm
Stamp 2	Ø 14 step 100 mm x 100 mm
Stamp 3	Ø 14 step 100 mm x 100 mm
Stamp 3	7 bars Ø24 length 240 cm where are the foundation pillars
Stamp 4	Ø 14 step 100 mm x 100 mm
Stamp 5	7 bars Ø24 length 240 cm where are the foundation pillars

Fig. 9 – The slab reinforcement distribution.

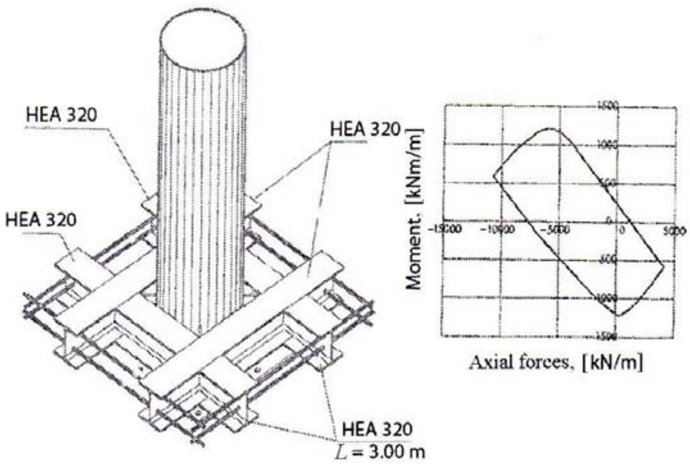


Fig.10 – Column anchorages.

The foundation of buildings and base of columns (anchor) is of slab type. The slab is a 50 cm plate, reinforced both in the upper and lower part, between the two layers, being placed the pile anchorages (Fig. 10).

The upper plate will be cast in formwork supported by metal extensible posts, at the necessary height, depending on the height of columns and insulators (Fig. 11).

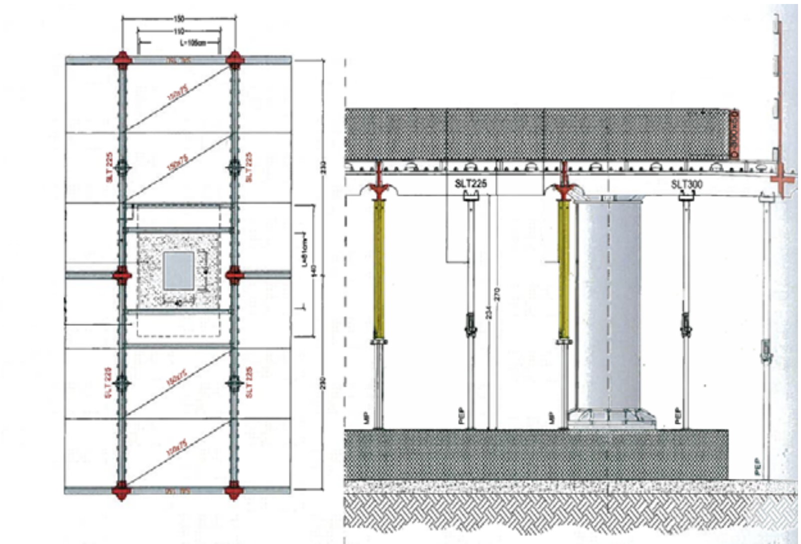


Fig.11 – Formwork support.

The manufacturing processes for each base are the followings:

a) execution of a levelling screed of about 15 cm;
b) positioning the formwork sides (perimeter);
c) placing of lower reinforcement;
d) positioning the anchor elements and upper reinforcements;
e) pouring concrete in formwork;
f) after the concrete sets, 40 piles will be laid;
g) mounting the upper plate formwork;
h) positioning of reinforcement in the upper plate;
i) pouring concrete in the plate.

The pillars were made mostly of metal, but concrete pillars were also used. Metal posts are of two kinds (Fig. 12). Reinforced concrete pillars are square with sides of 80 cm. Metal poles had better productivity over time, but they tried to optimize the reinforcement of concrete columns and thus the execution time was rated.

The seismic isolators used the friction pendulum type (Fig. 13). The pendulum friction support makes use of the characteristics of a pendulum to expand the dynamic response of a structure, while the friction between the pendulum and concave surfaces destinated to dissipate the seismic energy. The friction surface is covered with a resistant and non-corrosive material, such as teflon. The response period depends on the radius of a concave surface. The friction curvature radius measures 4 m, the equivalent damping is minimum 20% and the shift will be ±260 mm with a maximum axial load of 3,000 kN. Insulator fixtures differ, depending on insulator type and pole which it is mounted. Insulators are formed of two 360 mm diameter concave plates.

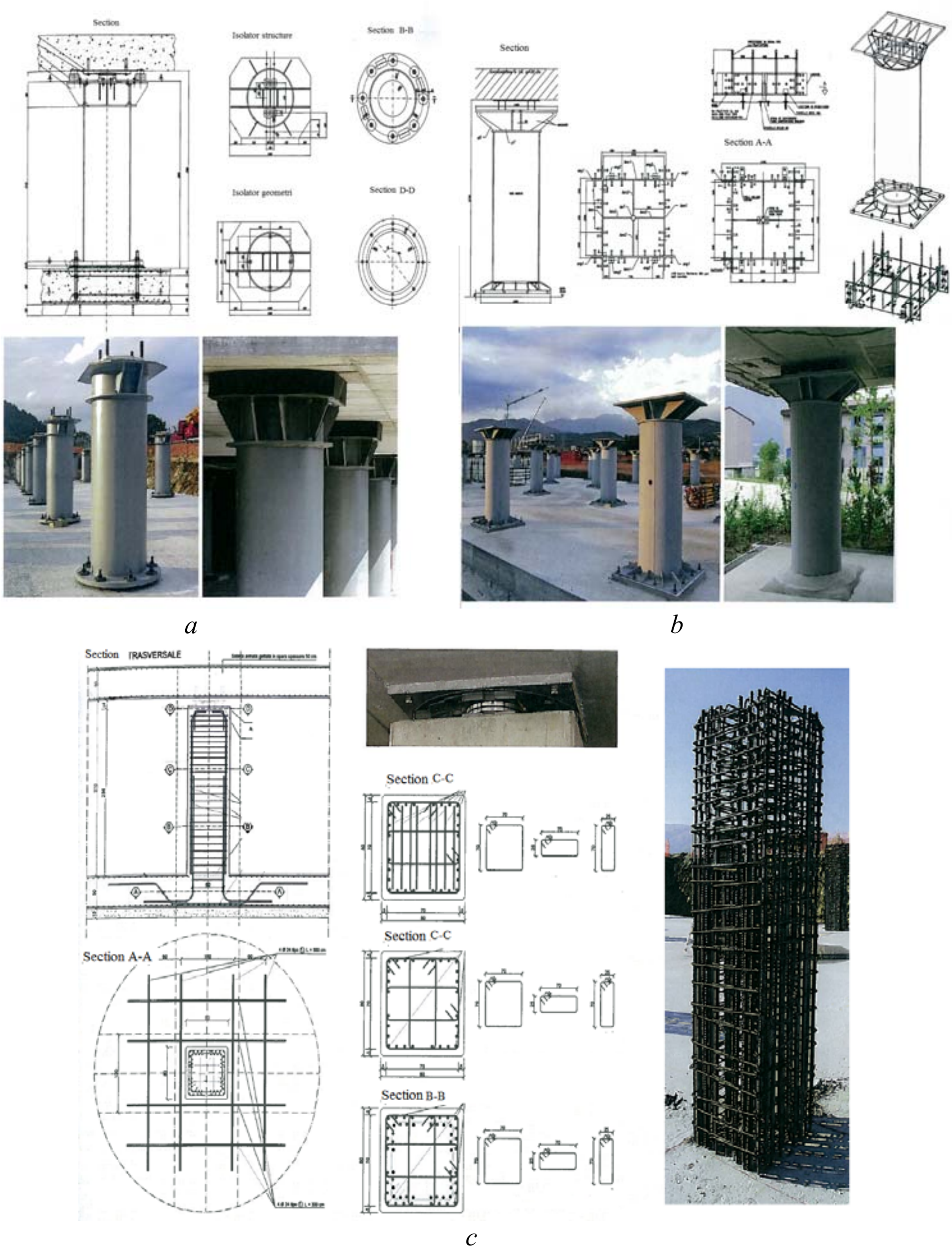
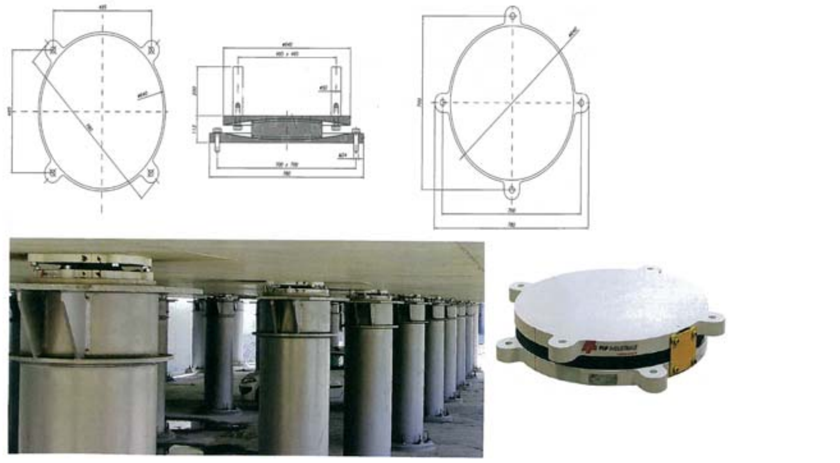
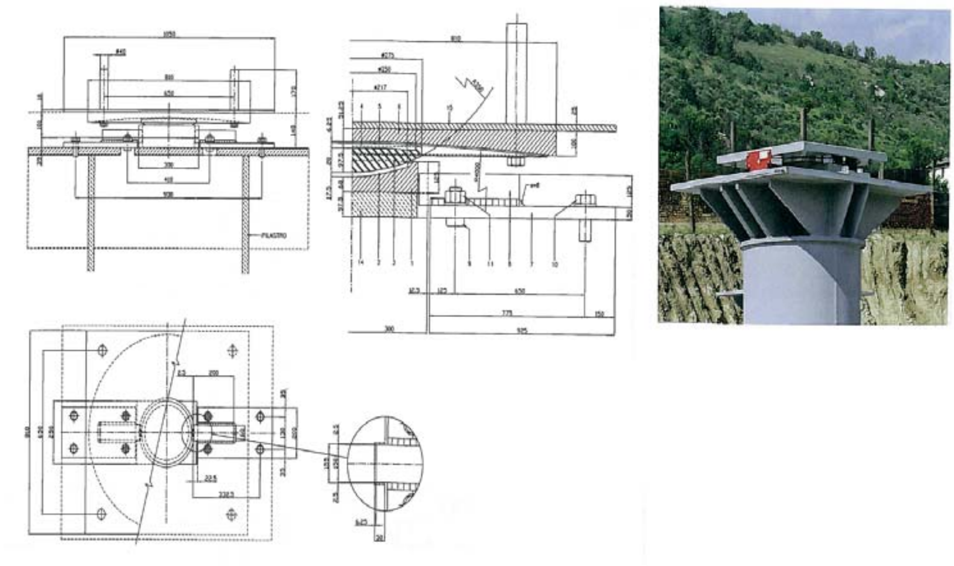


Fig. 12 – Column type: *a*, *b* – metal pillars; *c* – concrete pillars.



a



b

Fig. 13 – Seismic isolators using friction pendulum type: *a* – with two curves; *b* – with a single curve.

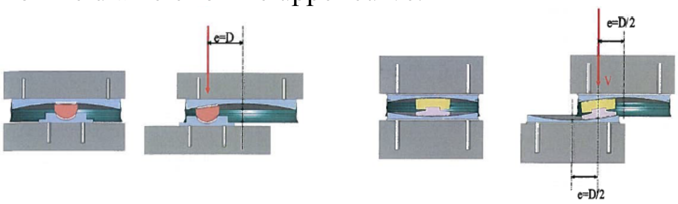
Seismic isolators may be

a) friction pendulum isolators with a single curve;

b) friction pendulum isolators with two curves.

The difference between the two types of insulators is the eccentricity of the horizontal force produced by the building weight.

Insulators with a single curve of friction (Figs. 13 *b*, 14 *a*) have the pendulum placed on a fixed support (pillar) and the concave curvature is fixed above the superstructure; in this case the eccentricity of the gravity force will be equal to half of the diameter of the upper curve.



a *b*

Fig. 14 – Seismic isolators using friction pendulum type:
a – with a single curve; *b* – with two curves.

Insulators with two friction curves (Figs. 13 *a*, 14 *b*) consist of two concave curves between which a pendulum is allowed to move freely. The eccentricity of the gravitational force in this case is one quarter of the diameter of the upper curve.

In this project, there were used 66% seismic isolators with a single curvature and 34% seismic isolators with two curves.

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ANALIZA SOLUȚIILOR DE RECONSTRUIRE A ORAŞULUI AQUILA, ITALIA, DUPĂ CUTREMURUL DIN 2009

(Rezumat)

Cutremurul este o catastrofă naturală imprevizibilă determinată de frecarea plăcilor tectonice. Lucrarea prezintă rezultatele studiilor privind distrugerile şi consecințele cutremurului din 6 aprilie 2009 produs in Italia, când o mare majoritate a clădirilor din oraşul Aquila au fost distruse. În continuare, în articol sunt prezentate măsurile de reconstruire, soluțiile de izolare seismică propuse şi utilizate la construcțiile noi.