Seismic insulation of the base for buildings with masonry structures

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Abstract. The purpose of this application is to see whether or not it is cost-effective to insulate the base of ordinary houses, made of load-bearing masonry. Certainly, the isolation of the base is suitable for structures of high importance, as well as historical monuments, but the common man does not live in a structure of high importance. Is the solution cost-effective for the average person? To test this hypothesis, we proposed a low structure (GF + 1) of confined masonry, located in a seismic area (Bucharest, ag = 0.30g, Tc = 1.6 sec) urban. The example is a multifamily duplex home.
The proposed structure being low, its own vibration period is small enough to be located in the area of maximum dynamic amplification in the response spectrum. For the simplified analysis we analysed starting from the hypothesis of a seismic force represented by the equivalent lateral force, according to the provisions of P100-1/2013. The basic concept of base isolation, respectively the decoupling of the structure from the foundation ground, also implies the increase of the own period sufficiently so that the structure is no longer in the area of maximum dynamic amplification of the response spectrum.

1. Study cases

1.1. Structural solution and some considered data
The structure is a duplex multifamily house, GF + 1 height regime (2 levels) in masonry type solution confined with reinforced concrete columns and belts. The material used in the masonry washers is of the Porotherm30St type, 30 cm thick (manufacturer's and material's website: http://www.wienerberger.ro/porotherm-30-sth.htm) with M10 type mortar and type plaster. Ceresit CT 63 3 mm thick on both sides. The concrete used is type C20 / 25 and the reinforcements taken into account are type S355 with periodically hot profiled profile (PC52). The level height is 3 meters both on the ground floor and upstairs. The solution for closing the roof is of the non-circulating terrace type (in order to be a roof, however, a payload of 1 kN/m² was taken into account, considered to be a possible tendency for storage or rare circulation). The floors are made of reinforced concrete 15 cm thick, considering the maximum openings and the acoustic comfort necessary for a home. The location was considered in the city of Bucharest. It was considered a geotechnical study valid for sector 2, prepared by a specialized company (as an example) from conclusions taking the following values: pconv = 370 kPa in the fundamental group (370 kPa in the special group) and Ks = 4.30 daN /cm³ (bed coefficient – Winkler coefficient). For masonry fck=3.49 N/mm² and E=500fck=1746.72 MPa and for concrete (C20/25) has the modulus of elasticity taken into account Eb = 15000 MPa considering that it works cracked.
1.2. Axis sketches

Figure 1 - Scheme axis in plan

Figure 2 - Location of reinforced concrete tie columns and masonry piers

2. Technical solutions presentation

2.1. According to the current design (P100-1/2013)

Figure 3 – 3D calculation structural model

Figure 4 - Interior wall foundation
Taking into consideration all the computations carried before, the conformation and pre-design of footings were made. Since the structure is symmetrical along a main axis (C axis), the importance of the structure is normal, the foundation ground is good and without problems of differential settlements, and the deformation restrictions in operation are negligible, we could use according to table 6.2. from NP 112/2014 the calculation method based on the conventional pressure on the ground.

The insulators were placed below the level of the foundation beams, modified so that they are in the form of rectangular beams of 40x80 cm. The insulators are of the HDS 1000x220 type. Under the insulators itself the foundation was made so that under each insulator is an insulated foundation. Due to the manufacturer's recommendation not to make completely insulated foundations, they were stiffened by a system of reinforced concrete beams arranged as in the figure below.

| Mode | Periods (sec) | Participant mass Ux | Participant mass Uy |
|------|--------------|---------------------|---------------------|
| 1    | 0.118        | 71.857              | 0.000               |
| 2    | 0.098        | 14.985              | 0.000               |
| 3    | 0.096        | 0.000               | 88.040              |
| 4    | 0.042        | 6.329               | 0.000               |
| 5    | 0.035        | 2.023               | 0.000               |

**Table 1 - Fundamental vibration periods**

**Figure 5 – 3D calculation model with the foundation system**

The reinforcement of the foundations was summarized below, ignoring the constructive and assembly reinforcements. Fundamental own modes of vibration of the structure:

**Figure 6 - First vibration mode**

**Figure 7 - Second vibration mode**
2.2. *According to the current design (P100-1/2013) in isolated solution at the base*

The structure was modelled using the ETABS Nonlinear program v9.7.4 and V18, considering the seismic force in the elastic field, but keeping in mind the damping due to the damping elements. The shock absorbers used are of the HDRB (High Damping Rubber Bearing) type with the properties of those from the technical data sheet from the ALGA manufacturer (www.alga.it). The location of the insulators was designed to be on the main directions.

The insulators were placed below the level of the foundation beams, modified so that they are in the form of rectangular beams of 40x80 cm. The insulators are of the HDS 1000x220 type. Under the insulators itself the foundation was made so that under each insulator is an insulated foundation. Due to the manufacturer's recommendation not to make completely insulated foundations, they were stiffened by a system of reinforced concrete beams arranged as in the figure below. The tie columns were reinforced more strongly to increase the load-bearing capacity of the uprights as can be seen in the table. The increased efforts of the marginal uprights in particular show the rigid solid behaviour of the house. The reinforcements for the foundations under the insulators were calculated as isolated foundations, required at the maximum axial forces in the insulators, and their stiffeners, the beam system was calculated in the completely unfavourable hypothesis in which two of the insulators stand in place while the others are loaded, with the maximum shear force at the base of the structure.

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**Figure 8** - Positioning the insulators under the structure

**Figure 9** - The foundation system of seismic insulators

**Figure 10** – 3D view of the calculation model of the foundations under the insulators
The reinforcement of the simple concrete block that represents the "isolated" foundation of the seismic insulator is reinforced considering a central support (insulator) that has in the console two halves of the foundation block, uniformly loaded with the maximum pressure registered at its surface (N/A from the table above).

Proper modes of the structure isolated at the base:

Table 2 – Fundamental vibration periods

| Mode | Periods (sec) | Participating mass Ux | Participating mass Uy |
|------|--------------|-----------------------|-----------------------|
| 1    | 2.602        | 99.934                | 0.056                 |
| 2    | 2.601        | 0.056                 | 99.943                |
| 3    | 1.626        | 0.010                 | 0.000                 |
| 4    | 0.119        | 0.001                 | 0.000                 |
| 5    | 0.109        | 0.000                 | 0.000                 |
| 6    | 0.075        | 0.000                 | 0.000                 |

As can be seen, the period increased a lot, passing the maximum dynamic amplification factor following the design spectrum. However, the calculations being made with the method of equivalent lateral force, the efforts increase significantly both in the infrastructure and in the superstructure, the advantage of the increased period being practically absent. But it is relevant that the isolation at the base brought a significant increase of the fundamental own period, moving it away from the dangerous zone of the great dynamic amplification. It is also observed that the mass participation factor on x and y has increased significantly, being approximately 100% of translation in both directions. Thus, it is observed how the torsional tendency of the structure due to the different rigidities on the two directions is cancelled by the insulation at the base, which forces the structure to behave like a rigid solid that can only take over translation.

The fundamental mode 1 of vibration in isolated solution is observed to have a much longer period and amplitude of movement than the uninsulated version of the house. The strictly translational behaviour of the movement is also observed.
2.3. Alternative base insulation solutions

For a more general study we tried different other models of seismic insulators. Thus, we tried to replace the HDRB type shock absorbers with lead core insulators, as well as friction pendulum type insulators. Because each insulator model has other dynamic damping characteristics, we had different seismic forces. This is also observed by the fact that the fundamental period of the system is longer in this case, going lower on the spectral acceleration curve.

Although there are small differences between the 3 types of insulation, they are practically not very big, in itself the efforts remain at about the same level.

2.4. Alternative base insulation solutions – response spectrum method
Since the lateral force method can only be applied under some aspects of regularity in plane and elevation, as well as with restrictions on the importance class, we made tests using the response spectrum method. We can thus compare the modelling efforts with the lateral force equivalent to those obtained from the response spectrum method and we obtain the following variation graphs:

![Figure 21 - Axial forces](image)

![Figure 22 - Bending moments](image)

![Figure 23 - Shear forces](image)

It can be seen that the axial effort differs very little (practically a few decimals), while the bending moment and the shear force decrease significantly in the method of spectral calculation compared to the method of statically equivalent lateral force.

3. Comparative results

3.1. Proper periods of vibration

The fundamental proper period from the isolated variant is recommended to be as long as possible in order not to be in the area of dynamic amplification of the response spectrum. Although the period is quite far from the control period (corner, \( T_c = 1.6 \) seconds) it is not far enough to greatly reduce the seismic effects.

| Mode | Unins | Ins | Isol/Unins | difference % |
|------|-------|-----|------------|--------------|
| 1    | 0.118 | 2.602 | 22.05      | 2105.21      |
| 2    | 0.098 | 2.601 | 26.52      | 2551.68      |
| 3    | 0.096 | 1.626 | 16.91      | 1591.13      |
| 4    | 0.042 | 0.119 | 2.81       | 181.37       |
| 5    | 0.035 | 0.109 | 3.11       | 210.5        |

![Figure 24 – Fundamental periods](image)
3.2. Lateral level displacements
The values of the relative lateral side displacements increase significantly, but they do not approach the limits imposed by P100-1 / 2013, respectively 0.5% relative displacement in the Service Limit State, and 2.5% in the Ultimate Limit State. Summarized below are the values from the two calculation hypotheses (uninsulated structure and seismically isolated structure):

[Figure 25 – SLS Drifts](image)

[Figure 26 - ULS Drifts](image)

3.3. Effects on superstructure, steel consumption
There is a significant increase in stress (bending moments and shear forces), as well as a strong increase in axial stress in the peripheral amounts (in the area of seismic insulators) while in other areas the axial stress decreases significantly, in some cases becoming almost negligible. The steel consumptions generated by the additional efforts of the Bending Moment and the Shear force type are due to the participation of the reinforcements from the columns and the eventual reinforcements for the Shear force from the masonry joints from the first level of the structure.

[Figure 27 – Reinforcement consumption in piers](image)

3.4. Effects on foundations, steel consumption
The foundations are practically "doubled" by the insulation system of the base, because both at and above the insulators, a structure with rigid diaphragm behaviour must be created. Considering the openings large enough for the beams over the insulators and the fact that they are practically simply supported on the entire opening, the supports being only the insulators at the end, their efforts are very large, requiring suitable reinforcements. Usually, in order to diminish their free length, the so-called "sliding supports" are mounted at equal distances, which have the role of taking over strictly vertical loads, sliding freely on some Teflon surfaces. Since the purpose of this application was to check if the insulation system of the base is profitable, I chose not to have such equipment for which I did not find the price, strictly arranging the 4 insulators in the corners of the house. The consumption of materials increases even more considering that the foundation under the insulators must be as rigid as possible, thus ensuring the co-flatness of the insulators.
4. Remarks

4.1. Profitability

The idea of the application started from the simple question "is it profitable to insulate the base of masonry houses?". For example, considering some purely statistical calculations, we chose a structure large enough to make the need for this additional investment feasible. Cost-effectiveness consists of cost, so below are summarized the additional consumption of necessary materials (except labour, transportation, formwork, and any other additional cost).

The investment of the house was approximately at about 250,000 euros, so that the total cost of insulation of about 28,000 euros represents only 11.20% of the total value. The impact of the additional cost seems significant, but an earthquake does not only damage the structure. Considering, for example, the most direct effects, the destruction of material goods (computer technology, displays, damage to paintings or decorative objects) whose value can be high, the insulation system can become useful. A structure has a lifespan of about 50 years.

4.2. Profitability

4.2.1. Architecture.

The interface with the architecture of an isolated structure at the base is mainly related to the problematic connection between the land and the structure. The problem is that although the structure must have the ability to move about 50 cm from the ground during the earthquake, while usually there must be easy access. A solution would be, as we proposed in the foundation detail of the insulator, a solidarity of the sidewalk and the access stairs with the concrete slab on the ground floor, so that the movement of the structure happens simultaneously with the movement of the access. Another problem related to architecture is that under the structure there must be a gap in which the structure can move freely. This basically generates a kind of ditch around the building, which can be quite unsightly. One solution could
be to wrap and cover this ditch between the structure and the ground with a kind of deformable "apron" made of rubber or other materials that allow movement. The problem with this solution would be that the material can degrade significantly during an earthquake (including the aging of the material and the climatic actions that can affect its performance), requiring its change in such an event. The thermal insulation of the structure can also be problematic, given that the foundation over the insulators can act as a thermal bridge between the two subassemblies.

4.2.2. Installations
The installations of the insulated structure at the base must have the capacity of free movement without generating losses of substances (water, gases). These can be achieved by building below the level of the board the foundation at level 0 of an installation chimney, up to which water, gas and electricity resources can be included in the usual way. At the interface between the superstructure and the substructure can be arranged cables and pipes with high capacities of elastic deformations, whose cost is paradoxically less than or equal to the usual installations. In order to prevent accidental spills of substances as well as the maintenance or change (if necessary) of the flexible connections, an access must be provided at their level, having a hole in the plate from level 0 for visiting the buried installation chimney. For greater flexibility, an automatic system closure system can be provided in the event of an earthquake, requiring a minimal investment in an accelerometer mechanically connected to a valve system.

4.3. Final remarks
The base insulation system is a very efficient system for reducing the seismic impact from all points of view.

Benefits:
- reduces or even eliminates structural damage or their size
- diminishes or even eliminates the damages of the non-structural elements
- diminishes or even eliminates material damage
- reduces the social impact of the earthquake (even if an earthquake exceeds the level of the one designed according to the code valid at that time, the structure will have a behavior clearly superior to a structure dimensioned in the post-elastic field of behavior)
- increases the life of the structure (limiting structural damage eliminates the need for consolidation and thus increases the life without the need for intervention)
- allows uninterrupted operation (if the structure is a registered office of a legal entity for example)

Disadvantages:
- the initial cost of the investment increases
- the execution duration increases due to the additional foundation system
- the average recurrence interval of earthquakes in Romania is relatively long, making potential investors skeptical about the need for such a system

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