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(Research Article)

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Base isolation retrofitting design for the existing 2-story stone building and its Conversion into a 3-Story kindergarten

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Abstract

Recently the Armenian Missionary Association of America (AMAA) has approached the author of this paper with the request to carry out base isolation retrofitting design for the existing 2-story building with stone bearing walls and to simultaneously convert it into a 3-story kindergarten. In Armenia seismic isolation of existing buildings is becoming a more common method of providing protection from earthquake damage. Thanks to the author's works in nowadays Armenia is well known as a country where seismic (base and roof) isolation systems are widely implemented in construction of new and retrofitting of existing buildings. The number of seismically isolated buildings per capita in Armenia is one of the highest in the world – second after Japan. The paper given below emphasizes that Armenia achieved significant results also in local manufacturing/testing of seismic isolation laminated rubber-steel bearings (SILRSBs). Several remarkable projects on retrofitting by base isolation of the existing buildings like apartment, school, hotel and hospital buildings are briefly mentioned in the paper to demonstrate the retrofitting experience accumulated in Armenia. Based on the gained experience further developments take place and unique base isolation structural concepts and technologies created by the author are applied more and more to the existing buildings. In this paper base isolation retrofitting design and analysis by the Armenian Seismic Code for the 2-story building with stone bearing walls is described. This will be a first application of base isolation retrofitting technology to an existing stone building with simultaneous increase of the number of its floors by one. The other important factor is that applied structural concept allows retrofitting by base isolation when reconstruction works in superstructure and construction of the additional 3-rd floor were going on in the same time.

Keywords: Base isolation strategy; Existing buildings; Seismic protection; Seismic retrofitting; Structural concepts; Low-cost technology; No interruption of the buildings' use; Seismic Code analysis

1. Introduction

The retrofitting technique using base isolation has great potential for rehabilitation of ordinary civil structures such as apartment blocks and critical facilities such as schools, hospitals. The works on development and research of seismic isolation technologies were initiated by the author in 1993. Since then, during a period of 28 years about 63 buildings and structures have been designed with application of base or roof isolation systems. Of these designed buildings the total number of already constructed and retrofitted buildings or those currently under construction and retrofitting in Armenia has reached 56 (Fig. 1). Among them there are bathhouses, private residences, school buildings, clinic and hospital buildings, business and commercial centers, hotels, apartment buildings and International Airport "Zvartnots". The number of seismically isolated buildings per capita in Armenia is one of the highest in the world – second after Japan. In [1] it is stated that: "Armenia remains second, at the worldwide level, for the number of applications of such devices per number of residents, in spite of the fact that it is still a developing country".

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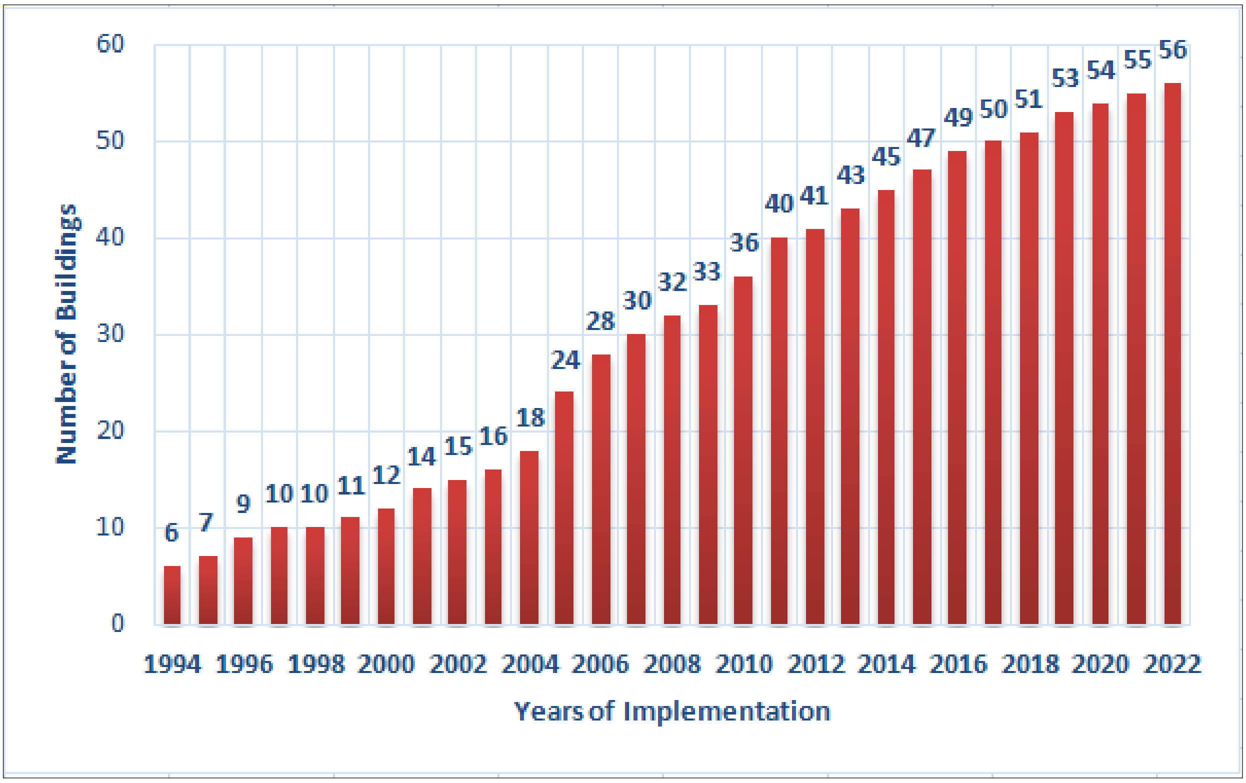


Figure 1 Number of seismic (base and roof) isolated buildings newly constructed or retrofitted in Armenia by years

Together with that SILRSBs different by their shape and dimensions, as well as by damping (low, medium and high) were designed and about 5500 SILRSBs were manufactured in the country, tested locally and applied in construction (Fig. 2).

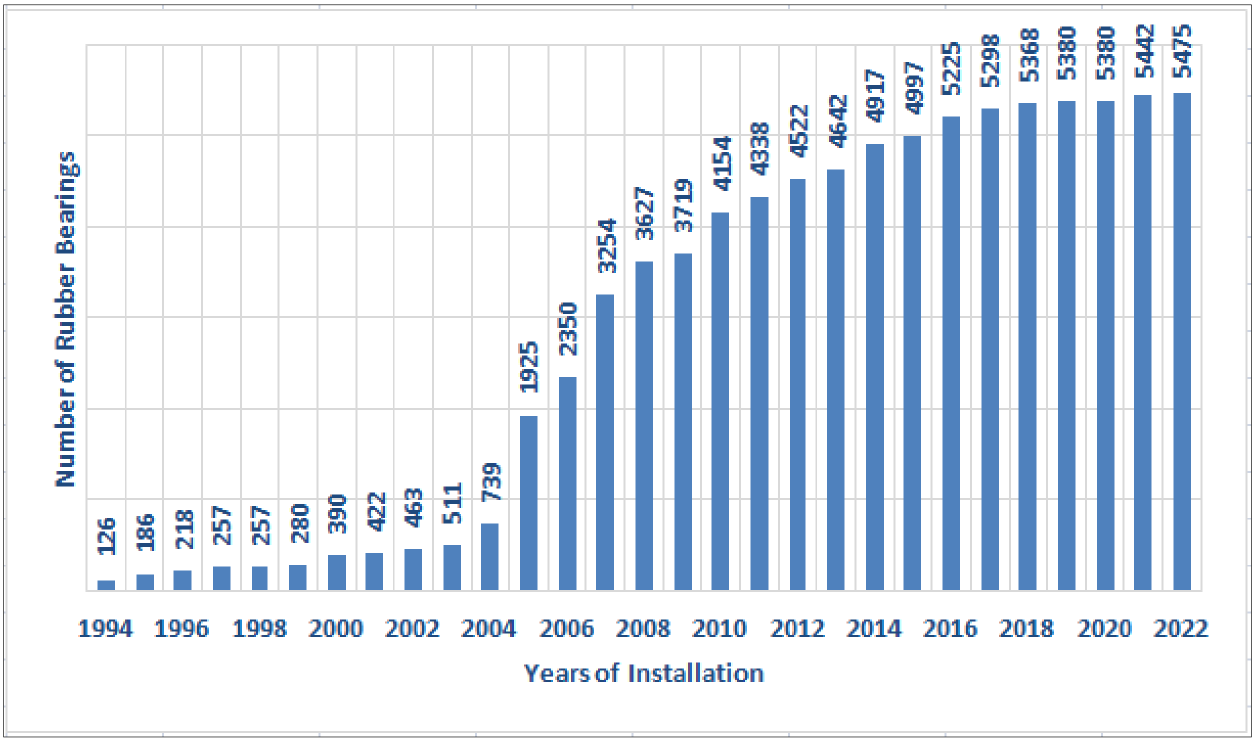


Figure 2 Number of rubber bearings installed in the newly constructed or retrofitted buildings in Armenia by years

Several remarkable projects on retrofitting by base and roof isolation were developed and implemented using technologies created by the author of this paper. One of them is retrofitting by base isolation of a 5-story stone apartment building (Fig. 3a) in the city of Vanadzor (Armenia). The operation was made without resettlements of the occupants. World practice provides no similar precedent in retrofitting of apartment buildings. The project was completed in 1996 [2].

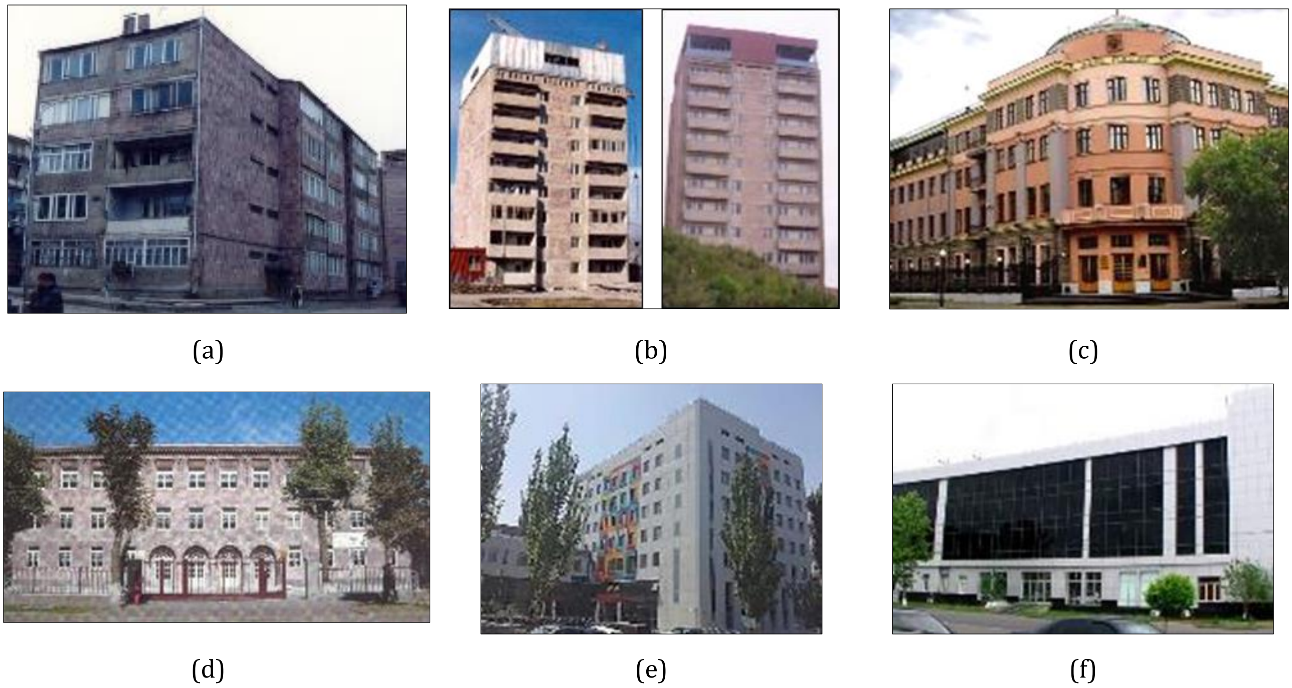


Figure 3 Projects on retrofitting by base and roof isolation utilizing different seismic isolation strategies developed by the author of this paper and implemented in armenia and russia

The next technology was utilizing the developed method of an additional isolated upper floor (AIUF) acting as a vibration damper. This technology of roof isolation was used in earthquake protection design and implementation for two existing reinforced concrete (R/C) 9-story standard design frame buildings (Fig. 3b) also in the city of Vanadzor. The projects were implemented in 1996-1997 [3]. Then by the end of nineties, another project initiated by Prof. Eisenberg and Dr. Smirnov [4] on retrofitting of about 100 years old 3-story stone bank building was implemented in the city of Irkutsk (Russia) with increasing of the number of stories up to 4 (Fig. 3c). It was emphasized by them that for retrofitting the existing bank building using base isolation they have implemented the method developed in [2] by the author of this paper who provided Russian and Chinese colleagues with all the needed drawings, photos, video film related to the retrofitting works carried out in Armenia. The other project is retrofitting of the 60-year-old 3-story stone school building which has historical meaning as well as a great architectural value (Fig. 3d). Unique operations were carried out to install the isolation system within the basement of this building and to preserve its architectural appearance. The project was implemented in the city of Vanadzor in 2002 [5, 6].

By given above brief information on several projects an objective is pursued to demonstrate experience in the field of retrofitting by base isolation of existing buildings with stone bearing walls, as well as of earthquake protection by roof isolation of existing R/C frame buildings. Later, the author has developed and proposed principally new structural approaches for base isolation of the existing R/C frame buildings with and without shear walls. Thus, further developments have taken place for retrofitting by base isolation and unique operations on retrofitting of the 8-story Hematology Center Hospital Building (Fig. 3e), constructed in Yerevan about 45 years ago, were accomplished. The seismic isolation of this existing building was created at the basement level. Detailed description of all phases for cutting the columns and shear walls and placing SILRSBs of the same sizes and physical/mechanical parameters are given in [7]. Results of analysis of this retrofitted building by the Armenian Seismic Code and the time histories are presented in [8].

The next strategy is retrofitting by base isolation of about 55-year-old 4-story R/C industrial frame building with its simultaneous reconstruction into a 6-story hotel building (Fig. 3f). This building is also located in Yerevan. New original technology on retrofitting by base isolation was developed and applied to this building and the results of its analysis in accordance with the provisions of Armenian Seismic Code and also time history analysis are discussed in [9]. SILRSBs with high damping of about 15% were used. Created solution is proposed for the first time and envisages placing the seismic isolators around the existing columns and then gradual cutting these structural elements. Operations are designed to be performed for the existing columns in several stages.

The given paper focused on retrofitting design of the existing 2-story building with stone bearing walls constructed in Stepanakert. Structural concept of retrofitting was developed for this building based on the acquired experience briefly described above. Base isolation interface for this building is designed at the level of basement floor. The building is analyzed based on the provisions of the Armenian Seismic Code.

2. Base Isolation Retrofitting approaches for the Existing Buildings with load-bearing walls

Isolation of structures from horizontal ground motions is gradually becoming a more common method of providing protection from earthquake damage. It is practicable to design the isolation system so that the structure responds elastically to the design level earthquake. Thus, repair cost should be greatly reduced, and continued serviceability of the structure assured. The rehabilitation of existing structures by the insertion of isolators at foundation level has been carried out on historic buildings such as the Oakland City Hall, San Francisco City Hall [10, 11], Salt Lake City and County Building [12, 13, 14], etc. For these, isolation may provide the only viable means that is not unduly intrusive and damaging for the appearance of the building.

The first retrofit of existing 5-story stone apartment building, as it was mentioned above in Introduction to this paper (see Fig. 3a), has been carried out in Armenia in 1995-1996 [2, 15]. The developed structural concept aims at retrofitting an existing building using a simple and innovative working approach [10, 16] according to the technology created by the author of this paper (Patent of the Republic of Armenia #579). This is a unique and pioneering seismic isolation project the idea of which was to furnish this building with seismic isolation by gradually cutting the isolators into the load-bearing walls made of tuff stones at the level of foundation upper edge by means of a two-stage system of R/C beams. SILRSBs are located by upper and lower recesses provided by annular steel rings bolted to outer steel plates which are connected to the reinforcement in the upper continuous and lower foundation beams; the isolators themselves are not bolted to the structure. This method of connection helps to minimize the cost of the isolators themselves and simplifies their installation on site [17]. Because the bearing is simply located in a recess, no tapped holes for bolted connections are needed in the endplate. The side, top and bottom rubber cover layers ensure the steel plates are protected from corrosion. This project was accomplished without re-settlement of the dwellers. There has been no similar precedent in the world practice of retrofitting apartment buildings.

After this successful start other project was developed and implemented in Armenia in 2001-2002 for retrofitting of the 60-year-old existing 3-story stone school #4 building (see Fig. 3d). The base isolation system was created at the level of the school basement in the middle part along the height of its load-bearing walls made of tuff stones [5, 6]. This approach implied some differences in retrofitting of the school building in comparison with that of the apartment building. In the case of the school building the lower continuous beams were structurally connected to the bearing walls of the basement. This afforded a possibility to strengthen the bearing walls by lower continuous beams before cutting the building and passing its weight through the seismic isolators to the bearing walls of the basement. Such structural solution permits the bearing walls of the basement to reliably carry the concentrated vertical loads and does not worsen their behavior and stress-strain state compared to other known solutions mentioned above [12, 13]. The unique operations were carried out to install SILRSBs and the technique of installation is especially important for the considered building, which has a historical and architectural value. First, the building's external appearance should not be disfigured under any circumstances. Second, not a single stone of the façade should fall when making openings in the bearing walls. One may have to deal with three different situations in making openings in the existing walls of the basement [6, 10]. The relatively simple case is when the opening has the part of existing wall above it. In this case there is no need to use any additional supports, as the strength of the wall above the opening is enough to avoid collapse. A more complicated situation for making openings arises when any of the existing beams or girders is crossing the space of the opening. In this case one of the ends of the existing beam loses its support and it is necessary to create temporary supports to carry the dead load of the existing building. The operation should be performed very carefully to avoid any damages in the superstructure after making openings in the existing walls. The most complicated case is when the opening does not have any part of the existing wall above it. For the subject matter school building such situations occurred at the entrance, where openings had to be made just beneath the columns and the arches. The arches had to be temporarily supported before starting to make the openings. Then the opening under the column should have been gradually made using temporary mechanical jacks. During every step of implementation in such complicated cases of retrofitting it is necessary to take care of the condition of the existing structures to prevent development of any damages, as these structures are part of the valuable architectural appearance of the building.

For the above-mentioned projects, the medium damping rubber bearings (MDRBs) with the damping of about 8-9% and the high damping rubber bearings (HDRBs) with the damping of about 13-15% from neoprene have been designed by the author of this paper. Medium or high damping rubber bearings are a simple, economical means of providing isolation. They have the low horizontal stiffness required to provide a long vibration period (typically 2 sec) to a structure mounted on such bearings. Their vertical stiffness is high, which minimizes rocking of the structure during an earthquake. The damping needed to limit the displacement of the structure and reduce the response at the isolation frequency is incorporated into the rubber compound, and so generally no auxiliary dissipation devices are needed. The service life of the bearings is expected to be several decades [18], and they should require no maintenance. Many projects throughout the world have installed seismic isolation systems based on such type of bearings [19, 20, 21].

3. Structural Concept of Retrofitting by Base Isolation of the existing 2-story building with stone bearing walls

Retrofitting design of the 2-story building under consideration (Fig. 4) was developed by the author of this paper in 2022. This project will be implemented in the city of Stepanakert.

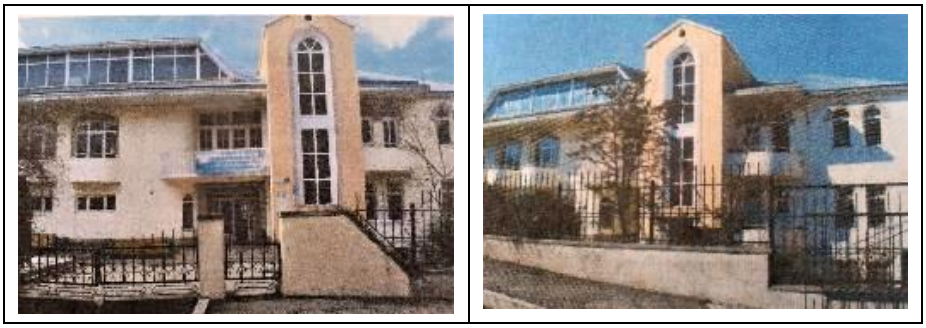


Figure 4 Views of the existing 2-story building with stone bearing walls to be retrofitted by base isolation

The building has rectangular plan with main dimensions of 30.2×19.7 m and with non-symmetric layout of the interior load-bearing walls. All walls have a thickness equal to 400 mm. The building has two exterior and one interior longitudinal load-bearing wall, as well as two exterior and two interior transverse load-bearing walls. The building has a basement only within the limits of the two right-side spans. The rest part was filled in with the ground (Fig. 5) up to the mark -0.08. The basement slab at the same mark (as well as the slabs of the first and second floors) was made of the precast reinforced concrete hollow-core panels, which have the thickness equal to 220 mm.

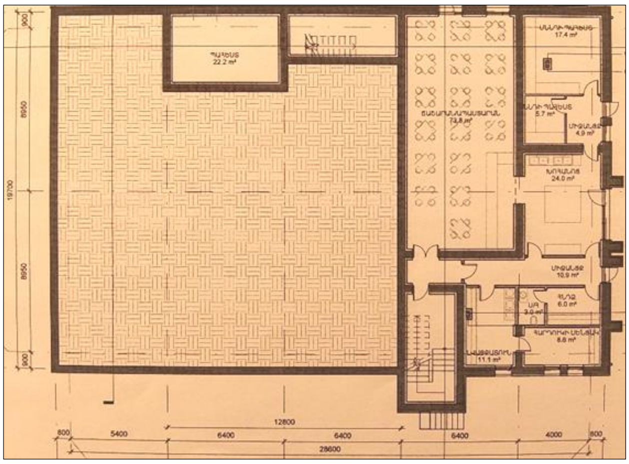


Figure 5 Plan of the existing 2-story building with stone bearing walls

For design of isolation system along all the exterior and interior load-bearing stone walls of the building the method of retrofitting by base isolation according to the above-mentioned Patent of the Republic of Armenia #579 was used. The developed base isolation method for existing buildings involves placing of seismic isolators at the level of basement in the middle part along the height of its load-bearing walls solves the problem in the following manner (Fig. 6). According to the developed by the author innovative technology, openings with certain spacing are made in the basement load-bearing walls to accommodate lower reinforcement frames with seismic isolator sockets. It is very important that two adjacent openings in the walls are not made simultaneously. Binding reinforcement lower frames are passed along both sides of the bearing walls through already installed reinforcement frames of the lower pedestals. Then the latter are concreted after placing of seismic isolators in the lower sockets to form lower pedestals. Upper sockets and upper reinforcement frames are placed on the isolators, passing along both sides of the bearing walls upper binding reinforcement frames through already installed upper reinforcement frames of the upper pedestals. Then the latter are concreted to form the upper pedestals. When concreting the frames of pedestals, ends of the binding reinforcement frames are left free beneath and above the seismic isolators. These free ends of reinforcing bars are tied to each other by the additional reinforcement frames of the adjacent lower and upper pedestals of seismic isolators.

Then the parts between pedestals are concreted thus forming lower and upper continuous beams along all load-bearing walls of the building's basement (see Fig. 6). The parts of the existing walls, which at this point remain between seismic isolators, must be then removed creating gaps and the building is hence separated from its foundation, being linked to it only by the seismic isolators. Parts of walls existing between seismic isolators should be cut off beginning from the middle of the building plan and continuing to its periphery. This will allow avoiding cracks at the top of the building considering the vertical deformations in SILRSBs during cutting of the walls.

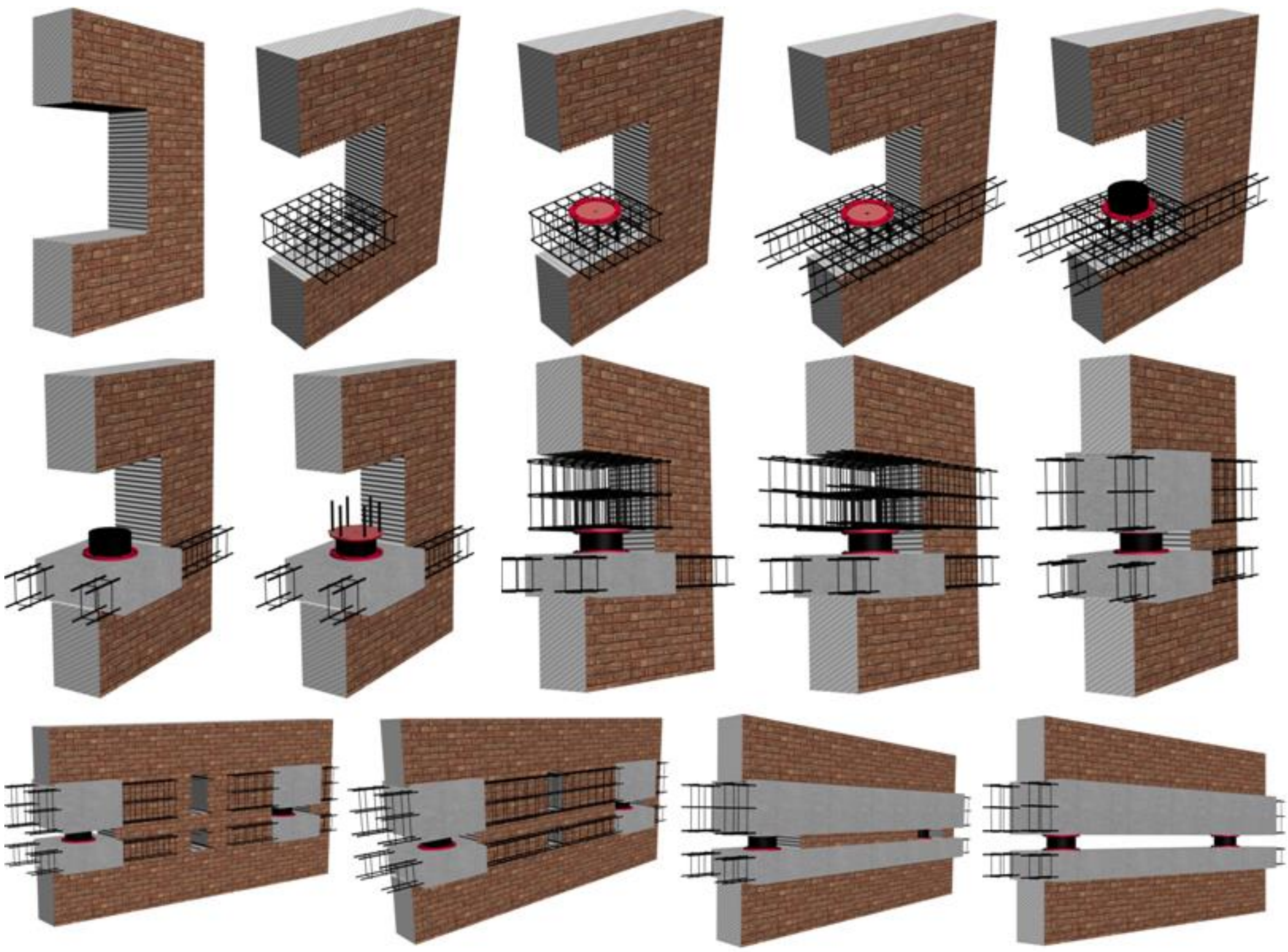


Figure 6 3D views of the seismic isolation system installation stages in the existing building with stone load-bearing walls

To create the seismic isolation system according to the described above technology it was decided to excavate the soil and, thus, to provide extension of the basement throughout the whole built surface of the building. From Figure 7 one can see that after excavating the soil the real picture of location of all the bearing walls was finally revealed.

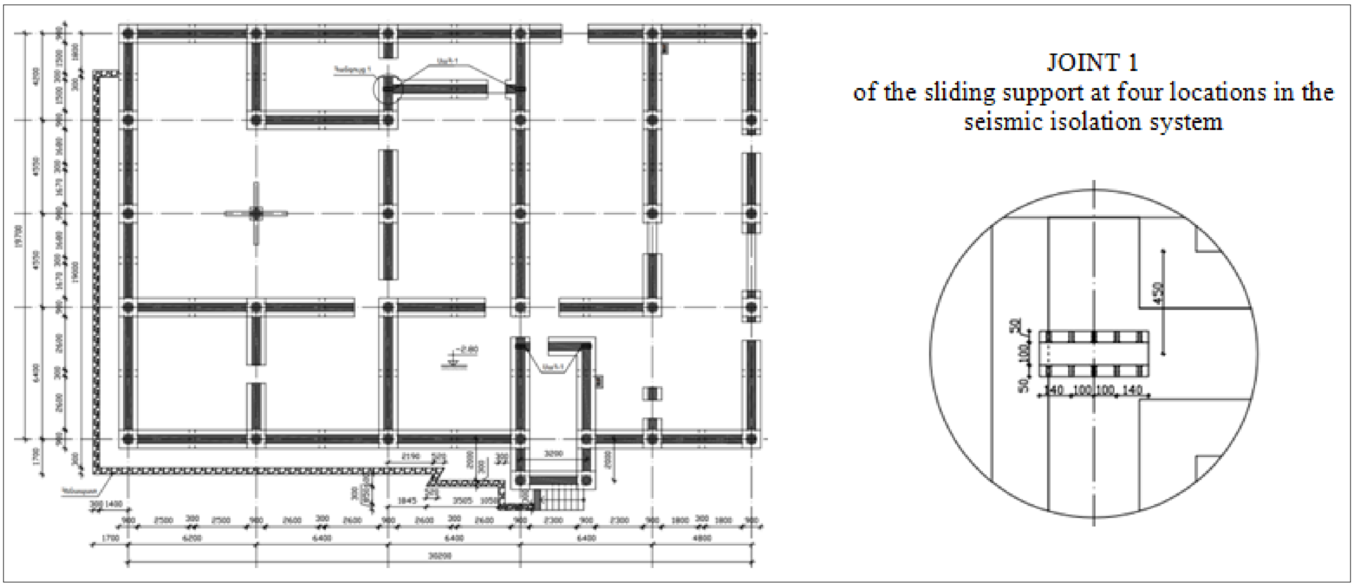


Figure 7 Plan of the lower pedestals with located on them SILRSBs and plan of the lower beams along the all load-bearing walls in the basement of the existing 2-story stone building

This operation gave the possibility to design the scheme of location of 33 SILRSBs and 4 sliding supports in seismic isolation interface of the building under consideration. In this particular case of the 2-story stone building the dimensions of the openings are equal to 900×1100(h) mm and the spacing between the centers of the openings (or between the seismic isolators) varies and comprises 4200 mm, 4550 mm, 4800 mm, 6200 mm, 6400 mm (see Fig. 7). Vertical elevations of the isolated building in longitudinal direction are shown in Figure 8.

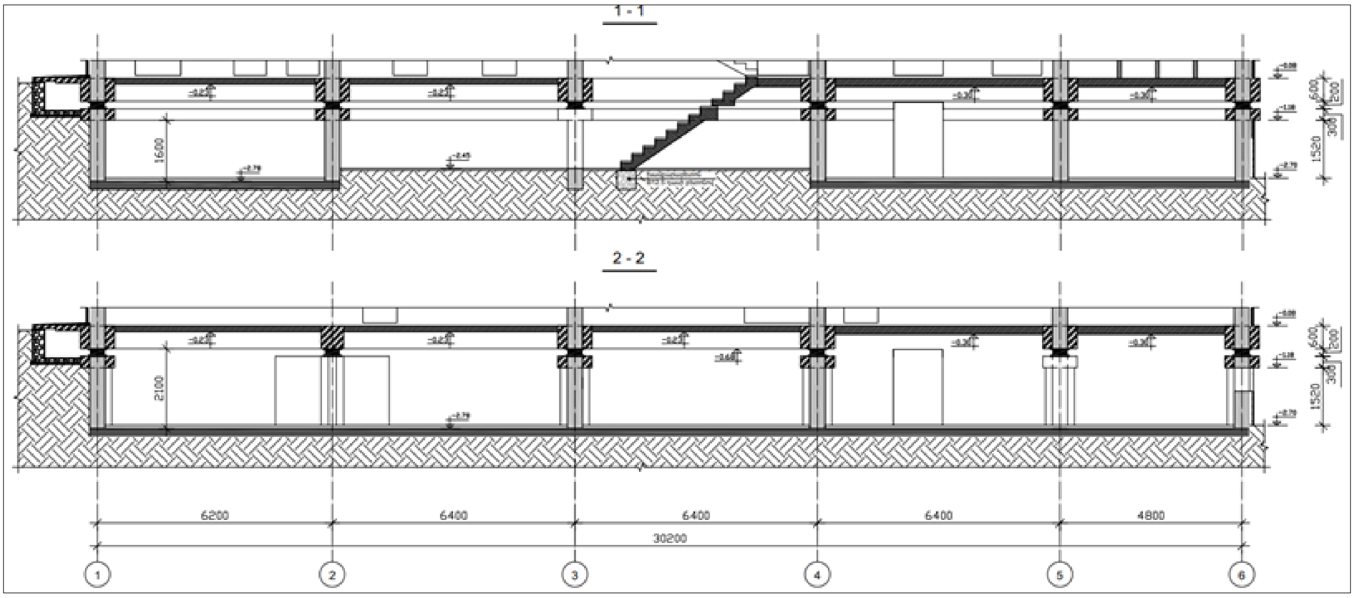


Figure 8 Vertical elevations 1-1 and 2-2 of the base isolated 2-story stone building in longitudinal direction

From the vertical elevations in Figure 8 one can see that the base isolation system consists of the lower continuous beams with the height of 300 mm to be constructed below the isolation interface, the gap (200 mm) where the SILRSBs are located and the upper continuous beams with the height of 600 mm to be constructed above the isolation interface. Thus, base isolation system will be constructed between the marks -1.18 and -0.08. At the mark -0.08 between the axes “1”-“4” a new monolithic slab was designed, which have the thickness equal to 150 mm. The width of the lower and upper continuous beams from the both sides of the existing load-bearing walls is the same and equal to 250 mm. To tie these beams to the walls and to each other design envisages drilling holes of diameter 20 mm in the existing walls and placing reinforcing bars of diameter 16 mm in these holes (for lower beams in one level and for upper beams in two levels) using polymer-cement mortar. As no existing walls were found along the axes 2, a column with four short shear walls around it was designed here (see Fig. 7 and 8).

The bearings with no horizontal stiffness, which we marked as BNHS (sliding supports), are envisaged in the design mainly at the wall crossing where the longitudinal walls are located out of the building axes (see Fig. 7). To install them the openings should be made with dimensions of 500×800(h) mm where the BNHS must be temporarily fixed. Then, by the analogy with the above described method of installation of SILRSBs, the lower reinforcement frames are installed, and the binding reinforcement frames of the lower continuous beams are connected to them. After concrete under the lower part of BNHS the similar operations should be made above their upper part (Fig. 9).

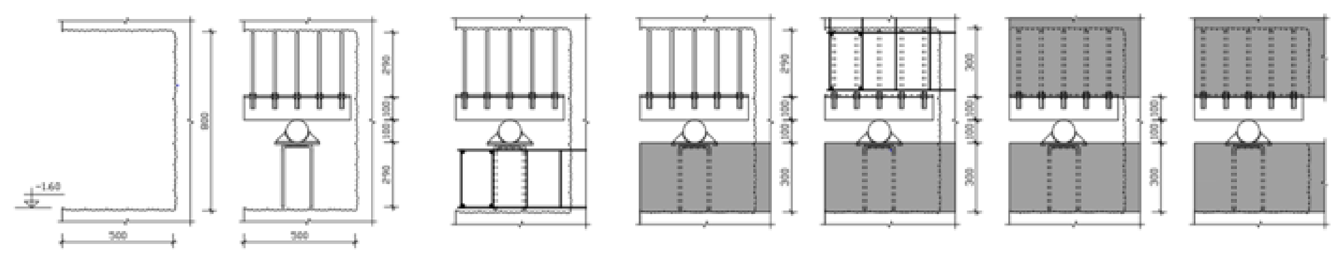
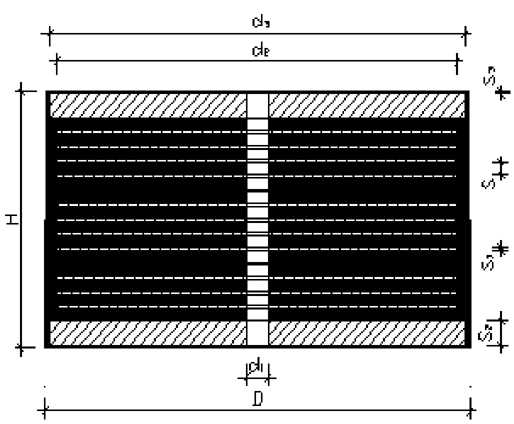


Figure 9 Stages of installation of BNHS in seismic isolation system of the existing 2-story building with stone load-bearing walls

Special attention needs to be paid to the stairs leading to the basement of the building. There is a 20 mm gap envisaged in the design between the upper 4 stairs and lower 8 stairs (see Fig. 8, vertical elevation 1-1). The main purpose of this gap, as well as the 200 mm gap of isolation system is to ensure unhindered movement of the superstructure, as well as effective action of the seismic isolation system and accommodation of its horizontal displacement during any seismic impact.

4. Parameters of the Used Seismic Isolation Laminated Rubber-Steel Bearings and results of their testing

As it was mentioned above the seismic isolation system of the considered building is designed at the level of its basement (see plan of the basement floor in Fig. 7). SILRSBs of the same type and sizes were used to make the seismic isolation system. Total 33 SILRSBs were used with aggregate effective horizontal stiffness equal to K_{eff}=0.81×33=26.73 kN/mm. These are manufactured in Armenia by "Shahnazaryans" LLC according to the Republic of Armenia Standard HST 261-2007 with the sizes and physical/mechanical parameters given in Figure 10.



External diameter of the bearing (D): (380 ± 2.0) mm;
Internal diameter of the bearing's central hole (d_1): (19 ± 1.0) mm;
Height of the bearing (H): (202.5 ± 2.5) mm;
Thickness of the rubber layers (S): (9 ± 0.1) mm;
Diameter of the steel shim plates (d_2): (360 ± 0.5) mm;
Thickness of the steel shim plates (S_1): (2.5 ± 0.1) mm;
External diameter of the upper and lower flanges (d_3): (376 ± 0.5) mm;
Thickness of the upper and lower flanges (S_2): (20 ± 0.2) mm;
Thickness of the upper and lower flanges' protective layer (S_3): (2 ± 0.1) mm;
Mass of the bearing: (77.5 ± 2.5) kg;
The bearing must withstand a maximum (design) permissible vertical loading of 1500 kN;
Shear modulus of the bearing's rubber must be (0.97 ± 0.15) MPa;
Vertical stiffness of the bearing: no less than 300 kN/mm;
Horizontal stiffness of the bearing: (0.81± 0.1) mm;
The bearing must withstand a maximum (design) permissible horizontal displacement of 280 mm, without causing cracks greater than 3 mm deep and 6 cm long;
Shore A hardness of the bearing: 70 ± 5 points;
Damping coefficient of the bearing: 10-15%.

Figure 10 Dimensions and physical/mechanical parameters of the seismic isolation laminated rubber-steel bearing

Testing of SILRSBs was carried out also in accordance with the mentioned Standard. Different loading systems were designed by the author to test simultaneously two rubber bearings with diameters of up to 380 mm, or one rubber bearing with a diameter of 580 mm, under horizontal and vertical loadings. They were capable of producing up to 1000 kN of force on the bearings in horizontal direction and up to 2000 kN in vertical direction.

The system used for this particular project (Fig. 11) consisted of two columns, upper and lower beams, a steel platform movable in the horizontal direction and a horizontally immovable upper plate. The bearings were compressed by vertical force through a hydraulic jack, which was located in the frame and the axis of which coincided with longitudinal axes of the frame and bearings. The horizontal actuator was positioned in such a way that its longitudinal axis was in the same horizontal plane with the internal movable plate.

The tests were carried out by “Melkumyan Seismic Technologies” LLC in conformity with the accepted methodology through application of alternating cyclic horizontal loading. During the displacement control shear test isolators were subjected to constant vertical force and gradually increasing horizontal displacement that reached the maximum value corresponding to the design displacement. Figure 11 also shows the deformed rubber bearings tested up to the displacement of 190 mm using a testing facility designed for the combined shear and compression tests of bearings with diameters of up to 380 mm. Results of the testing are presented in Table 1.

Figure 11 Facilities in the laboratory named after the author of this paper and designed by him for testing of different types of the seismic isolation laminated rubber-steel bearings

Table 1 Some results of testing of SILRSBs manufactured by "Shahnazaryans" LLC for the project on retrofitting by base isolation of the existing building with stone load-bearing walls in Stepanakert

Marking of SILRSBs	Date of testing	Modulus of elasticity, Mpa	Vertical stiffness, kN/mm	Shear modulus, Mpa	Horizontal stiffness, kN/mm
S01-S02	25.06.22	562.0	505.6	0.998	0.898
S03-S04	27.06.22	396.2	356.4	0.758	0.682
S05-S06	30.06.22	494.0	444.4	0.798	0.718
S07-S08	30.06.22	621.4	559.0	1.013	0.911
S09-S10	04.07.22	749.4	674.2	0.967	0.870
S13-S14	08.07.22	513.0	461.5	0.883	0.795
S19-S20	12.07.22	578.3	520.2	0.962	0.865
S23-S24	19.07.22	470.8	423.5	0.889	0.800
S25-S26	21.07.22	462.1	415.7	0.872	0.785
S27-S28	21.07.22	416.8	375.0	0.942	0.847
S29-S30	27.07.22	408.3	367.3	0.865	0.778
S31-S32	27.07.22	491.6	442.3	1.012	0.911
S33-S34	11.08.22	588.5	529.4	1.006	0.905
S35-S36	11.08.22	615.6	553.8	1.007	0.906
S37-S38	29.08.22	586.7	527.9	1.008	0.907
S39-S40	29.08.22	581.6	523.3	1.004	0.903
S41-S42	29.08.22	407.5	366.6	0.886	0.797

After completion of testing all the SILRSBs were labeled and sent to construction site. Examples of the labeled bearings are shown in Figure 12.

Figure 12 Views of the tested and labeled SILRSBs; these isolators will be located by upper and lower recesses provided by annular steel rings bolted to outer steel plates which are connected to the reinforcement in the upper and lower continuous beams; the isolators themselves are not bolted to the structure

Having all testing results and based on the carried out analysis on uniform distribution of the stiffness in seismic isolation interface a drawing was developed showing markings of SILRSBs to be placed at each location (Fig. 13). This strategy would lead to a somewhat more uniform distribution of the horizontal seismic forces and help ensure that the isolation system's center of stiffness is close in plan to the projection of the building's center of mass. This minimizes the excitation of torsion vibrations of the building on the isolators during an earthquake.

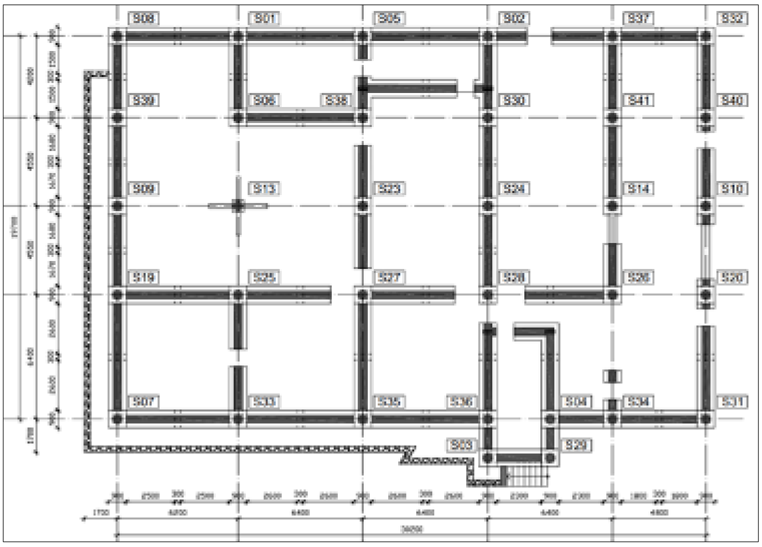


Figure 13 Plan of seismic isolation interface showing markings of SILRSBs to be placed at each location

From the Figures 7, 8, and 13 one can see that in plan of the building along the left and lower exterior walls a small retaining wall is envisaged. This was needed considering that ground level here is higher than the level of seismic isolation interface. The distance between the mentioned exterior walls and the retaining wall is equal to 950 mm. This gap is covered by a monolithic cantilever slab coming out of the upper continuous beams, and again, it will ensure unhindered movement of the superstructure, as well as effective action of the seismic isolation system and accommodation of its horizontal displacement during any seismic impact. Together with that the cantilever slab will prevent the accumulation of debris and protect against atmospheric precipitations. The final design view of the building is shown in Figure 14. Architectural design for this project was developed by "Storaket" Architectural Studio.

Figure 14 Design view of seismic isolated building converted into 3-story kindergarten

5. Analysis of the base isolated structure with stone bearing walls after its conversion into 3-story building

Analysis of the seismic isolation system and the whole structure was performed in accordance with the Armenian Seismic Code RABC 20.04.2020 assuming the following parameters:

- Seismic zone 3 and soil category II;
- Soil conditions coefficient is K_0=1.0 and the site prevailing period of vibrations $0.3 \leq T_0 \leq 0.6$ sec;
- Permissible damage coefficient for determining displacements – K_{1z}=0.8;
- Permissible damage coefficient for analysis of the superstructure – K_1=0.7;
- Coefficient of seismicity – A=0.3.

After multiple criticisms by the author of this book of the former edition of the Armenian Seismic Code RABC II-6.02-2006 it was finally edited and converted into new edition RABC 20.04.2020 (the author was one of those who actively participated in preparation of this new edition by changing many of the provisions of the former edition). Namely, new edition now requires that any base isolated building should be analyzed applying the same permissible damage coefficient for analysis of the superstructure, as well as the isolation system and structures below it. In the given case permissible damage coefficient K_1=0.7 was used in analysis. It is also assumed that vibration period (T) of the base isolated building should be around 2 sec. According to the new RABC 20.04.2020 horizontal displacement of the base isolation system must be calculated by the formulas (5) and (32) of the Code:

$$D= K_{1z}\times(T/2\pi)^2\times A\times K_0\times[\beta(T)/B(n)]\times K_1,$$

Where dynamic coefficient β (T) depends on soil category and determined by the formulas given in the Code. In this case β (T) =0.81. B(n) depends on the damping of isolation system and for the value of 10% Code suggests this coefficient equal to 1.3. Thus:

$$D=0.8\times(2/6.28)^2\times300\times(0.81/1.3)\times0.7=10.62 \text{ cm.}$$

Based on the provision of item 349 of the RABC 20.04.2020 the obtained value of horizontal displacement must be multiplied by a factor 1.1. At the same time based on the provision of another item 345 to provide high reliability of seismic isolation system it is required to apply one more factor 1.1. Thus, the calculated value of horizontal displacement must be multiplied by a factor 1.21.

$$D_t=10.62\times1.21=12.85 \text{ cm.}$$

Obtained value of total horizontal displacement is smaller than the maximum permissible displacement suggested by the Armenian Standard HST 261-2007 (28 cm). This will provide high reliability of the designed seismic isolation system. According to the RABC 20.04.2020 total seismic force on the top of isolation system (base of superstructure) must be calculated by the formula (35) of the Code:

$$S_t=K_{eff}\times D_t=26.73\times128.5=3434.8 \text{ kN.}$$

To calculate the vibration period of the base isolated 3-story kindergarten building the masses of its floors were computed and the total mass M_t of the building was equal to 2711 t. According to the RABC 20.04.2020 vibration period for the base isolated 3-story building is determined by the formula (31) of the Code using the values of the total mass of this building (superstructure) and effective stiffness of isolation system:

$$T=2\pi\times\sqrt{}Q/(K_{eff}\times g)=6.28\times\sqrt{}2711/26730=2.0 \text{ sec.}$$

Using the obtained values, it is possible to calculate the magnitude of acceleration just above the seismic isolation interface:

$$a=S_t/M_t=3434.8/2711=1.27 \text{ m/sec}^2.$$

From this it follows that due to application of base isolation acceleration at the level of the first floor of the superstructure decreases by about 2.4 times in comparison with the input ground acceleration (3.0 m/sec^2). This is very typical result showing the high effectiveness and reliability of base isolated structures. Particularly, the superstructure of the kindergarten building will have no deformations due to moving during the earthquake as a rigid body. All the structural elements below and above the seismic isolation interface will work only in elastic stage. Analysis shows that the magnitudes of accelerations at the level of the slab just above the seismic isolation interface and at the top of the building are practically equal to each other.

6. Conclusion

Several remarkable projects on retrofitting by base isolation of the existing buildings like apartment, school, hotel, and hospital buildings are briefly mentioned in the paper to demonstrate the retrofitting experience accumulated in Armenia.

Retrofitting design for the existing 2-story building with the stone load-bearing walls is presented including conversion of this building into 3-story kindergarten. As a tool for retrofitting the base isolation technology is used. The innovative structural concept of retrofitting by base isolation is described in detail explaining retrofitting approaches for the existing buildings with load-bearing walls.

Total 33 SILRSBs were used in seismic isolation system. These are manufactured in Armenia according to the Republic of Armenia Standard HST 261-2007. Their dimensions and physical/mechanical parameters are given. Together with SILRSBs 4 bearings with no horizontal stiffness named BNHS are used.

Some results of analysis of the base isolated 3-story building with the stone load-bearing walls by the Armenian Seismic Code are given showing that the structural elements below and above the seismic isolation plane will work only in the elastic phase. Total horizontal displacement comprises 12.85 cm, period of vibration – 2.0 sec and acceleration at the level above the seismic isolation interface – 1.27 m/sec^2. An input acceleration of 0.3g at the foundation bed gets damped about 2.4 times in the superstructure.

Obtained results prove the high effectiveness of the created base isolation system and reliability of the building, which will suffer no damage under seismic impacts. Under the impact of the design level earthquake the inter-story drifts remain smaller than the permissible values.

Based on the extensive experience accumulated in Armenia it can be stated that comparison of the construction cost of retrofitting by the suggested design with the cost of conventional strengthening shows that significant cost savings (up to 5 times) could be achieved due to implementation of the created base isolation technology.

The time needed for performing of the construction works by the given design could be shortened for about 5 times in comparison with the time for conventional strengthening. Implementation of the elaborated design will not require interrupting of the reconstruction works in the superstructure of the 3-story kindergarten building.

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