Comparison of the Analyses Results of Seismic Isolated Buildings by the Design Code and Time Histories

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Abstract-Extensive implementation of seismic isolation technologies in Armenia provided a good basis for the development and inclusion of a separate chapter on seismic isolation of buildings in the last edition of the National Seismic Code RABC II-6.02-2006. This chapter is presented in the paper. Since 1994 during a short period of 19 years about 46 buildings and structures have been designed by the author of this paper 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 has reached 37. Information on some of these buildings is given in the paper. Based on the analyses carried out for the considered buildings it is emphasized that seismic isolation significantly reduces the maximum spectral acceleration, also proving to be cost effective and ensuring high reliability of their behaviour under seismic impacts. Seismic isolation techniques developed in Armenia lead to significant savings in construction costs. Several reasons for savings are mentioned in the paper. Comparison of the Code based analyses results with those obtained by the time history analyses indicates that the shear forces at the level of isolation systems, the maximum displacements of the isolators, and the maximum story drifts in the superstructures calculated based on the Armenian Seismic Code provisions are considerably higher than the same values calculated by the time histories. It is concluded that the Code needs a more accurate designation of reduction factors for seismic isolation systems. Corresponding suggestion is made in the paper for the Code revision.

Keywords- Seismic Isolated Buildings; Earthquake Response Analysis; High Reliability; Cost Savings; Time History; Seismic Code; Comparison of Results; Reduction Factors

I. INTRODUCTION

It is known that with the exception of some countries like Japan [1, 2], Italy [3], China [4], and currently also Armenia [5] the growth in the number of seismic isolated buildings worldwide is still quite slow. One of the reasons is the lack of provisions in seismic codes for such type of buildings. Hence, in order to successfully continue the works on implementation of seismic isolation in Armenia it was necessary to develop a code for the design of seismic isolation systems. The first attempt to develop such a code was undertaken in collaboration with TARRC. The proposed draft code consisted of three parts: A. Design of Overall Isolation System, B. Design and Type Testing of Rubber Isolators, and C. Manufacture and Quality Control Testing of Rubber Isolators [6]. This work was financed by the World Bank within the framework of the Armenia Earthquake Zone Reconstruction Project [7, 8] and was accomplished in 1995-1996. The proposed code was reviewed by Prof. Kelly and Dr. Tajirian. However, the draft code was not approved by the Ministry of Urban Development (MUD) of Armenia, as there was an opinion that the country already has a National Seismic Code that allows designing seismic isolation and there is no need to have a separate code for seismic isolation. So the MUD has decided to have the guidelines for seismic isolation of buildings and structures as an attachment to the National Seismic Code, instead of a separate code.

By the order of MUD, on the basis of the already proposed code for design of seismic isolation systems, the Guidelines for seismic isolation of buildings and structures were developed [9]. The Guidelines involved provisions on the types, calculation, design, and maintenance of the passive seismic isolation systems. Also examples of designing base isolated buildings were included in the Guidelines. Seismic isolation was established to mean isolation of buildings and structures against ground motions only in horizontal direction. The Guidelines stipulated that the system should display high resiliency allowing for great horizontal displacements (50-400 mm) without any damage. The design should also allow free access to each isolator and provide possibility to replace it without difficulties, if necessary.

The National Seismic Code of Armenia was developed after the collapse of the Soviet Union and its first edition was approved in 1994. This was the Republic of Armenia Building Code (RABC) II-2.02-94 titled Earthquake Resistant Construction: Design Codes. It contained some provisions regarding seismic isolation of buildings. However, they were not sufficiently detailed in order to be used by any design institution. Therefore, only the author of this paper being affiliated with the Research Centers of Scientific Research Institutes or Universities was able to analyze and design seismic isolated buildings. The lack of detailed provisions in the Code caused barriers for further development of seismic isolation systems in Armenia. It is well known that since 1994 seismic (base and roof) isolated buildings in Armenia were designed using very limited clauses of the RABC II-2.02-94 and also of the above mentioned Guidelines. There was only a Protocol of the MUD that gave the possibility to officially design and build seismic isolated buildings. Therefore, a separate chapter dedicated to the seismic isolation of buildings and structures was needed.
II. CHANGES IN THE SEISMIC CODE OF ARMENIA REGARDING SEISMIC ISOLATION OF BUILDINGS AND STRUCTURES

There was a years-long discussion about the necessity of including the detailed provisions of the earlier developed draft code and Guidelines into the existing Code in effect. However, it was only in 2004 when efforts were undertaken to revise and prepare a new edition of the National Seismic Code. This offered a good opportunity for addressing the issue again. Moreover, the extensive implementation of seismic isolation technologies by the private companies provided a good basis for the development and inclusion of a separate chapter on seismic isolation of buildings in the new edition of the Code. The proposal was finally accepted by the MUD and for the first time in the history of Seismic Codes development in Armenia, the Chapter 10 – Buildings and Structures with Seismic Isolation Systems, was included in the new edition of the National Seismic Code RABC II-6.02-2006 [10] and was adopted by the Government of Armenia. Together with that in 2007 the MUD also approved the Guidelines for Design and Construction of Buildings with Application of Laminated Rubber Steel Bearings, as well as the Standard of the Republic of Armenia AST 261-2007 Seismic Isolation Laminated Rubber Steel Bearing. The Chapter 10 of the RABC II-6.02-2006 consists of five parts and their main content is presented below.

General provisions of this Chapter stipulate that its requirements cover both the design of newly constructed buildings and structures of various types, and the retrofit of existing buildings and structures, with application of seismic isolation laminated rubber steel bearings (SILRSB). They are placed between the foundation and superstructure (part of the structure above the seismic isolation) or between several lower stories and superstructure.

The design of the buildings and structures with seismic isolation systems shall be carried out in accordance with the terms of the technical specifications (TS) and Republican Standards (AST) meeting the requirements of the SILRSB application. The design shall provide for free access to each SILRSB and possibility to easily replace them. The service lifetime of SILRSB is warranted individually based on the terms of TS and RABC specified by the manufacturer.

The seismic isolation is used for buildings and structures with fundamental periods of natural oscillations within 0.1-1.0 sec for regular foundations (i.e. without seismic isolation) and no more than 3.0 sec for those with seismic isolation. By the structural concepts two types of seismic isolation systems are used: (i) systems located below the level of the pavement around the building (Fig. 1a); and (ii) systems located above the level of the pavement, but no higher than the second story level (Fig. 1b and 1c). The choice of the seismic isolation type is governed by the soil conditions and functional purpose of a given building.

The connections of utility lines with the structure shall not increase the seismic isolation system’s horizontal rigidity for more than 5% in case of horizontal movement. There shall be a seismic gap around the structure, sized at least one and a half times the design displacement for the structure’s free horizontal movement on seismic isolators. The preservation of the seismic gap over the service time of the structure shall be ensured by the design solutions on the erection of buildings. The gap between the lowest part of superstructure and topmost part of the foundation shall be large enough to allow for free vertical static and dynamic deformations of the seismic isolation system for the entire duration of the structure’s service time, and when earthquake induced horizontal displacement exceeds the design displacement by one and a half times. The fire safety rules shall be adhered to in the spaces where seismic isolation systems are housed.

The value of free oscillation period T for buildings and structures with seismic isolation systems with horizontal stiffness corresponding to the effective stiffness of the seismic isolators is determined by the following formula:

\[ T = \frac{2\pi \sqrt{\frac{Q}{K_{\text{eff}} g}}}{\pi} \]

where: Q is the aggregate vertical static load (weight of the superstructure); \( K_{\text{eff}} \) is the stiffness of the isolation system, which is equal to the sum of effective stiffness of the seismic isolators that comprise the system, as specified by the TS of the manufacturer or by AST; \( g \) is the gravitational acceleration.

The design horizontal displacement at the seismic isolation system level is determined by the formula:
where: $a$ is the expected values of the horizontal ground acceleration; $k_0$ is the soil conditions coefficient; $\beta(T)$ is the dynamic coefficient, which depends on soil category and the oscillation period. The values of the coefficient $B(n)$ are given in the Table 1 below. The value of $k_1^z = 1$ for seismic zone 1 ($a=200\text{cm/sec}^2$) and zone 2 ($a=300\text{cm/sec}^2$), and $k_2^z = 0.8$ for seismic zone 3 ($a=400 \text{ cm/sec}^2$).

If eccentricity exists between the seismic isolation system centre of rigidity and the superstructure centre of mass, then the value of total design displacement with consideration of seismic isolators’ torsion is equal to:

$$D_{\text{total}} = 1.1D$$

The total design displacement must be less than that of the seismic isolators, which corresponds to their effective stiffness $K_{\text{eff}}$ during the cyclic tests carried out in accordance with the manufacturer’s TS.

In analysis by accelerograms (time histories), the horizontal displacements at the level of the top of the seismic isolators shall be determined by the following formula:

$$D_a = \left(\frac{T}{2\pi}\right)^2 \tau(T, n)$$

where: $\tau(T, n)$ is the earthquake response spectra by the actual or synthetic accelerogram selected for the given construction site. For compilation of the $\tau(T, n)$, the value of the critical damping coefficient is assumed equal to the actual value of $n$, obtained during the SILRSB tests. For analysis by accelerograms, the value of $D_{\text{total}}$ is assumed equal to $D_a$.

The value of horizontal seismic transverse force generated during an earthquake at the top of the seismic isolators (base of the superstructure) is determined by the following formula:

$$S = K_{\text{eff}} D_{\text{total}}$$

The strength analysis of elements connecting seismic isolators to the superstructure, as well as those to the foundation is performed under action of the above defined horizontal force. The design value of the horizontal seismic load $S_k$ applied at the point $k$ of the superstructure with weight $Q_k$ is determined by the following formula:

$$S_k = \frac{S_k Q_k h_k}{\sum_{i=1}^{n} Q_i h_i}$$

where: $h_k$ is the height from the base of superstructure to the concentrated load $Q_k$. The values of the permissible damage coefficient $k_i$ for the superstructures of various structural concepts are defined in the RABC II-6.02-2006.

In analysis by accelerograms the seismic isolation systems can be modelled in linear or non-linear force-displacement relationship. For the linear seismic isolation system the structure is considered as a rigid body. For the non-linear seismic isolation system presented by bi-linear force-displacement relationship, the influence of higher modes shall be duly regarded. The linear model of seismic isolation is applied if all of the conditions mentioned below are met:

- the structural system of a building or structure is homogeneous;
- the period of the structure’s natural oscillations without seismic isolation is $\leq 0.6\text{sec}$;
- the relative eccentricity between the structure’s center of mass and the seismic isolation system’s center of rigidity does not exceed 0.01;
- isolators are placed in a single plane;
- the vertical stiffness of the isolator is at least 200 times more than its horizontal stiffness.

The non-linear model of seismic isolation system is applied in cases not covered by the above conditions, as well as if SILRSB with high damping properties (10% and more) are used.
For the structural solution along the superstructure height and in plan that meets the requirements of RABC II-6.02-2006, the superstructure shall be modelled as a vertical bar resting on seismic isolation system, rigidly tied with the ground (foundation) and having concentrated masses at floor slabs levels. In such case the rods between masses are assumed to be weightless, with horizontal stiffness equal to the sum of the horizontal stiffness of all vertical bearing elements at the given story level.

Footings under seismic isolators can be of strip and spread types. Spread footings shall be connected to each other with rigid ties. A horizontal frame bound with a rigid disc of the floor slab shall be arranged on the top of the seismic isolators. Its design model represents a continuous system resting on concentrated elastic supports. The frame shall be rigidly tied to the superstructure and have a design solution that prevents torques in its structural elements.

The seismic isolators in plan are placed with consideration of the building configuration and uniform distribution of vertical loads on them. The distances between seismic isolators or groups of seismic isolators shall not differ from each other by more than 1.5 times. The configuration of buildings and structures with seismic isolation systems shall be as simple as possible both in plan and along the height. Up to 12-storey buildings and structures may have height level differences of no more than the size of three stories (no more than 11 meters), as well as asymmetric geometric shapes in plan. In order to minimize the eccentricity between the centre of horizontal rigidity and the structure’s centre of mass projection on the SILRSB plane, the scatter of vertical loads on seismic isolators of the same stiffness shall not exceed ± 20%. It is allowed to use two or more SILRSB under the bearing structures of the superstructure.

### III. APPLICATION OF SEISMIC ISOLATION IN ARMENIA

Since 1994 during a short period of 19 years, about 46 buildings and structures have been designed by the author of this paper 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 has reached 37. Among them there are private residences, school buildings, a clinic building, a business centre, apartment buildings, and hotels.

The diagrams in Fig. 2 and Fig. 3 illustrate increase of the number of seismic isolated buildings and the number of rubber bearings manufactured and installed in Armenia by years, respectively. Products of the companies involved in manufacturing of seismic isolation bearings and the numbers of the bearings made by each company in different years are shown in Fig. 4. Based on the data collected from different sources [11, 12] it can be stated that the number of seismic isolated buildings per capita in Armenia is one of the highest in the world (Fig. 5). This was also mentioned in the Resolution adopted by participants of the 8th World Seminar on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures held in Yerevan in 2003. [13]

Thus, the seismic isolation technologies are being extensively developed in Armenia. The applications of seismic isolation took place in design and construction of up to 20-story multifunctional buildings. All these buildings are mainly of irregular shape in plan and along their height. Therefore, a new approach in analysis and design of such buildings was proposed by the author of this paper and applied in order to increase their seismic stability and to neutralize the rotation. [14]

The developed seismic isolation techniques are bringing to significant savings in construction and retrofitting costs and this fact has attracted the attention of the international professional community [15], as well as of many companies like Huntsman Corporation (Fig. 6), Tufenkian Hospitality, LLC (Fig. 7) Elite Group, CJSC (Fig. 8) and ITARKO Construction, CJSC (Fig. 9). Even the governmental program on providing apartments for young families has expressed an interest in construction of a base isolated building (Fig. 10).

![Fig. 2 Number of seismic (base and roof) isolated buildings, newly constructed or retrofitted in Armenia by years](image2)

![Fig. 3 Number of rubber bearings installed in the newly constructed or retrofitted buildings in Armenia by years](image3)
Fig. 4 Armenian companies specialized in manufacturing of seismic isolation rubber bearings, their products and production volumes in different years.

Fig. 5 Number of seismic isolated buildings per capita in different countries.

Fig. 6 Views of newly constructed 4-story base isolated apartment buildings in Gyumri.

Fig. 7 Design views of newly constructed 6-story base isolated hotel building in Dilijan (a) and 7-story base isolated commercial centre building in Yerevan (b).
Several reasons for savings in construction and retrofitting costs due to seismic isolation could be mentioned. One of them is that rubber bearings manufactured in Armenia cost significantly cheaper than bearings manufactured elsewhere in the world. This is conditioned by the lower labour cost, availability of rubber components in the country, as well as existence of several competing factories capable of manufacturing high quality rubber bearings with low (LDRB), medium (MDRB) and high (HDRB) damping.

Also, the provisions of the Armenian Seismic Code for seismically isolated structures are much more progressive in terms of analysis and design of superstructures of base isolated buildings. The matter is that this Code allows to somewhat decrease the resistance of the superstructure of an isolated building with respect to that of a building on a conventional foundation. As a result, a huge amount of reinforcement could be reduced in superstructures of R/C base isolated buildings designed in accordance with the Armenian Code. In addition, cross-sections of the bearing structures (columns, beams, shear walls) are smaller, and there is no need to apply high strength concrete for them. Therefore, large amounts of concrete and cement may also be saved in superstructures.

Thus, construction of ordinary (apartment) buildings and critical facilities (schools, hospitals, etc.) using seismic isolation costs 30-35% cheaper in comparison with the conventionally designed buildings. Much higher savings were attained in retrofitting of an apartment building and a school building. In these cases, due to seismic isolation, the cost of retrofitting was about two times less in comparison with the cost of conventional retrofitting.

IV. COMPARISON OF THE RESULTS OF ANALYSES BASED ON THE CODE IN FORCE AND TIME HISTORIES

The earthquake response analyses carried out for different buildings considered in this paper have shown that in comparison with the fixed base buildings, seismic isolation significantly reduces the maximum spectral acceleration, proving to be cost effective for the isolated structures and ensuring high reliability of their behavior under seismic impacts.
conditions in all the considered cases are good and the soils here are of category II with the predominant period of vibrations of not more than 0.6 sec.

Comparison of the Code based analyses results with those obtained by the time history analyses indicates that the shear forces at the level of isolation systems, the maximum displacements of the isolators, and the maximum story drifts in the superstructures calculated based on the Armenian Seismic Code provisions are considerably higher than the same values calculated by the time histories. To demonstrate these differences, some results of calculations for different buildings are given in Table 2.

Using the data of Table 2, the average values of Q, D and Δ were calculated for both cases and compared to each other. The results of comparison are as follows: horizontal shear forces calculated in accordance with the Code provisions are greater than those calculated by the time histories by 1.85 times, maximum horizontal displacements of isolation systems are larger by 1.89 times and maximum story drifts in superstructures – by 2.03 times in average. Obviously, the differences should have not been so large. This means some further steps should be taken to more realistically reflect the characteristics of seismically isolated buildings (including the reduction factors for isolation systems) in the design models for the calculations based on the Code. [16]

For zone 3, where the expected maximum acceleration is equal to as=400 cm/sec², as it has already been mentioned above, there are different permissible damage coefficients stipulated in the Code for base isolated structures. For the considered buildings, in particular, when their bearing systems consist of reinforced concrete frames, shear walls and horizontal rigid diaphragms-slabs, it is required to apply the permissible damage coefficient (reduction factor) of k_r=0.4 for superstructure and k_r=0.8 for seismic isolators and structures below the isolation plane.

Table 2 Some Results of Calculations for Different Base Isolated Buildings By The Armenian Seismic Code and By the Time Histories in Transverse (X) Direction

<table>
<thead>
<tr>
<th>Name of building</th>
<th>By the Armenian Seismic Code</th>
<th>By the time histories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q, kN</td>
<td>D, mm</td>
</tr>
<tr>
<td>6-story hotel building, T=1.98 sec</td>
<td>17078</td>
<td>215</td>
</tr>
<tr>
<td>7-story commercial centre building, T=1.88 sec</td>
<td>18659</td>
<td>225</td>
</tr>
<tr>
<td>10-story &quot;Our Yard&quot; building, T=2.04 sec</td>
<td>20950</td>
<td>220</td>
</tr>
<tr>
<td>16-story &quot;Our Yard&quot; building, T=2.06 sec</td>
<td>19380</td>
<td>202</td>
</tr>
<tr>
<td>11-story &quot;Cascade&quot; building, T=1.91 sec</td>
<td>21386</td>
<td>188</td>
</tr>
<tr>
<td>20-story business center &quot;Elite Plaza&quot;, T=2.04 sec</td>
<td>48281</td>
<td>279</td>
</tr>
<tr>
<td>14-story &quot;Arani&quot; building, T=2.00 sec</td>
<td>17860</td>
<td>218</td>
</tr>
<tr>
<td>16-story &quot;Arani&quot; building, T=2.15 sec</td>
<td>24835</td>
<td>202</td>
</tr>
<tr>
<td>13-story &quot;Dzorap&quot; building, T=2.00 sec</td>
<td>12831</td>
<td>217</td>
</tr>
<tr>
<td>16-story &quot;Dzorap&quot; building, T=2.12 sec</td>
<td>40654</td>
<td>210</td>
</tr>
<tr>
<td>18-story &quot;Northern Ray&quot; building, T=2.41 sec</td>
<td>96964</td>
<td>265</td>
</tr>
<tr>
<td>17-story &quot;Baghramian&quot; building, T=2.46 sec</td>
<td>51810</td>
<td>259</td>
</tr>
<tr>
<td>15-story &quot;Avan&quot; building, T=2.03 sec</td>
<td>44341</td>
<td>222</td>
</tr>
<tr>
<td>17-story &quot;Sevak&quot; building, T=1.98 sec</td>
<td>32092</td>
<td>215</td>
</tr>
</tbody>
</table>

Q – horizontal shear force at the level of isolation system; D – maximum horizontal displacement of isolation system; Δ – maximum story drift in superstructure.

Actually, the Code requires that any base isolated building of the mentioned type should be analyzed twice: first, by applying k_r=0.8 and the obtained results will serve as a basis to design the isolation system and structures below it, and then the second analysis should be carried out by applying k_r=0.4 and the derived results will serve as a basis to design the superstructure.

However, the data regarding the analyses of multistory isolated buildings provided in the RABC II-6.02-2006 indicates that the displacements of isolation systems, inter-story drifts and horizontal shear forces obtained by calculations of the base isolated buildings by this Code are close to the same values obtained by the time history analyses when the permissible damage coefficient (reduction factor) of k_r=0.4 is applied. However, in case if k_r=0.8, the Code based results are higher by a factor of about 2 in average. Therefore, the Code needs a more accurate designation of reduction factors for seismic isolation systems. At
this stage it is suggested to accept $k_r=0.6$ for zone 3 in the next edition of the Code, as a compromise solution.

V. CONCLUSIONS

The paper is dedicated to an important topic of seismic isolation of buildings and structures. The growth in the number of such buildings worldwide is essential as in comparison with the fixed base buildings, seismic isolation significantly reduces the maximum spectral acceleration, also proving to be cost effective for the isolated structures and ensuring high reliability of their behaviour under strong seismic impacts.

One of the conditions for rapid and wide application of seismic isolation in earthquake prone countries is availability of special provisions in seismic codes for isolated buildings. Extensive implementation of seismic isolation technologies in Armenia is a good example for further successful development and application of the created innovative structural concepts and design rules for developing countries. A separate chapter on seismic isolation of buildings in the last edition of the Armenian National Seismic Code RABC II-6.02-2006 is presented in the paper.

Since 1994 during a short period of 19 years about 46 buildings and structures have been designed by the author of this paper 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 has reached 37. Information on some of these buildings is given in the paper. It is emphasized that the developed seismic isolation techniques lead to significant savings in construction costs and several reasons for savings are mentioned in the paper.

The earthquake response analyses carried out for different buildings considered in this paper have shown that there is a need for further improvement of the Armenian Seismic Code provisions regarding the values of the reduction factors. Comparison of the Code based analyses results with those obtained by the time history analyses indicates that the shear forces at the level of isolation systems, the maximum displacements of the isolators, and the maximum story drifts in the superstructures calculated based on the Code provisions are considerably higher than the same values calculated by the time histories. It is concluded that the Code needs a more accurate designation of reduction factors for seismic isolation systems. Corresponding suggestion is made for the Code revision.

REFERENCES


Mikayel G. Melkumyan was born on June 10, 1951. He started his scientific and practical activity in 1973, immediately after graduation from the Civil Engineering Department of Yerevan Polytechnic Institute, carrying out both design works and experimental-theoretical research to study the behavior of various reinforced concrete structures under seismic actions. In 1983 he defended his thesis for the degree of Candidate of Engineering Sciences and began to lead the Department of Earthquake Resistant Construction at the Armenian Scientific–Research Institute of Construction and Architecture. After the Spitak earthquake of December 7, 1988 in Armenia, Dr. Melkumyan dedicated himself to the deep analysis of consequences of this and other earthquakes and reasons for widespread destructions of various buildings and structures.

From April 1990 through March 1991 he conducted research at the Institute of Industrial Science (IIS), University of Tokyo, where he was invited by Prof. Tsuneo Okada, Director of the Institute. On the basis of his experimental research works he created a new hysteresis model to describe the shear behavior of reinforced concrete structures (walls, diaphragms). As it is indicated in the Certificate granted to him by the IIS, this model and the formula proposed by him for calculation of horizontal stiffness of diaphragms were accepted in Okada and Nakano laboratory, and the model was incorporated in the computational software for earthquake response analysis of multi-storey frame buildings with predominance of shear deformation. It is also mentioned in the Certificate that this research work will have a considerable contribution to earthquake resistant construction and earthquake damage mitigation in the world.

After his return from Japan, from 1992 through 1996 he was a teaching Professor at the College of Engineering of the American University of Armenia, giving lectures on non-linear behavior of reinforced concrete structures and design principles thereof in earthquake resistant construction. At the same time he led the Earthquake Engineering Center of the National Survey for Seismic Protection under the Government of Armenia. From 1993 through 1997, having been approved by the Government for the position of Director, he managed the Spitak Earthquake Zone Reconstruction Project, financed by the World Bank. From 1993 he started his work on development and application of seismic isolation systems for buildings and structures in Armenia, in the meanwhile defending his thesis for the degree of Doctor of Engineering Sciences in 1997 on the subject “Formation of the Dynamic Design Models for Seismic Response Analysis of Reinforced Concrete Buildings and their New Structural Solutions”.

During a short period of time in 1995-1996, devoting himself to the challenge of increasing earthquake resistance of existing buildings, he developed two unique methods of protecting existing buildings from earthquakes through base isolation and isolated upper floor without interrupting exploitation of the buildings. His new technologies were successfully implemented in Armenia, where for the first time in the world a 5-story stone apartment building and over 60 years old 3-story stone school building, which had a historical and architectural value, were retrofitted by base isolation without evacuation of inhabitants and interruption of school functioning. Besides, for the first time seismic resistance of two existing 9-story apartment buildings of standard frame-panel design was enhanced by application of the isolated upper floor. These works are unprecedented in the world practice of earthquake resistant construction of the time.

Later on, his technology for seismic isolation of existing stone buildings (Patent of the Republic of Armenia № 579) was successfully applied in Russia during retrofitting by base isolation of a 100 years old bank building in Irkutsk city. Afterwards, the Government of Romania ordered a design for retrofitting about 180 years old municipality building in Iasi city, which he accomplished using the same technology.

His works in the fields of both non-linear behavior of reinforced-concrete structures and seismic isolation are well known to the international professional community by the weighty contribution to the science and practice of earthquake resistant construction. He has authored and co-authored 182 scientific works, including 13 books, 10 normative documents, and 12 inventions. As a principal structural engineer he has designed more than 80 earthquake resistant residential, civil, and industrial buildings. More than 100 of his scientific works have been published in international journals and proceedings of the World, European, and National Conferences in 27 countries of the world.

He is the President of the Armenian Association for Earthquake Engineering, the Vice-President of the International Association of CIS countries on Seismic Isolation, a Member of the Executive Committee of Anti-Seismic Systems International Society (ASSISi), a Member of the Saint-Petersburg Arctic Academy of Sciences, a Corresponding Member of Engineering Academy of Armenia, International Expert in Seismic Protection of Buildings and Structures of the Professional League of Experts of the CIS countries’ Commission on Earthquake Resistant Construction and Disaster Reduction, the Chairman of the National Technical Commission TC7 Anti-Seismic Devices under the Technical Committee CEN/TC340 of the European Committee for Standardization, an overseas Member of the Research Center of Earthquake Resistant Structures of the IIS, University of Tokyo, a Member of the European Association for Structural Dynamics and European Association for the Control of Structures.