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Preventive seismic strengthening and urban resilience

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Abstract

The article describes history, approaches and well-tested technologies, which have developed and have successfully applied for preventive reinforcement of insufficiently earthquake-resistant buildings of Petropavlovsk-Kamchatsky. This was required due to the short-term forecast of earthquake with M ~ 7.5 and in the corresponding of order of Russia Council of Ministers on upgrading the seismic resistance of housing stock and life facilities in Kamchatka. At that time technologies were based on the experience of restoring Tashkent after the earthquake of 1966, i.e. it were time-consuming, expensive and, most importantly, required a complete shutdown of the operation of buildings for a long time. Seismic evaluation and certification of housing stock (beginning with stone and large-block residential buildings) and earthquake resistance assessment of schools and hospitals buildings were carried out preliminarily. Several scenarios of probable disasters were developed as part of the disaster mitigation program. Then the Russian-Yugoslav JV "Andriakampacific" was specially founded to develop and implement advanced technologies into practice of strengthening the buildings without stopping their operation and evicting people. Advantages and disadvantages, results of our joint activity to reduce seismic risk in Kamchatka are described. Seems, the received experience is gaining new value today both for reconstruction after strong and damaging earthquakes, and for cases of combination of earthquakes with epidemiological hazards, as it was the case in Zagreb on March 22, 2020. This article is dedicated to the bright memory of my talented colleague and kind friend Prof. Bosko Petrovic.

Key words: Complex hazards, seismic strengthening, non-stop operation of building, risk reduction, resilience earthquake, preventive technologies

1 History and background

It would seem that the tragic aftermath of the earthquake in Tangshan, China on July 28, 1976 finally confirmed the impossibility for now to making the short-term forecast simultaneously the time, place and intensity of disastrous earthquakes. However, in 1985-1986, the director of the Institute of Volcanology (Far Eastern Branch of the Russian Academy of Sciences) S.A. Fedotov, announced an earthquake with M~7.5 predicted in the Avacha Gulf in the next five years, which would be destructive (I = VIII-IX according to EMS-98) for Petropavlovsk-Kamchatsky (next-Petropavlovsk), and achieved official recognition of this forecast. The corresponding order No2359 of the Council of Ministers of the Russian Federation "On increasing the seismic resistance of objects of the national economy of the Kamchatka region" was signed on November 21, 1986. Indeed, the seismicity of this urban area for average soil conditions on July 1, 1970 was increased from VIII to IX points with the high recurrence period (especially the earthquakes of intencity I = VII-VIII in 1952, 1959 and 1971) significantly reduced the seismic resistance of existing buildings. Fulfilling the order of the Government, more than 40 ministries and departments of the country, which own residential and office buildings in Petropavlovsk, have developed projects of seismic strengthening of their buildings. All these projects were considered unfit for implementation, because they were based on the experience of reconstruction of Tashkent after the earthquake of 1966 [1], where two methods of strengthening the load-bearing walls were used: double-sided shotcrete-concreting along the reinforcement grid or compressing the buildings along the contour with belts made of steel channels. The first method was time-consuming and expensive, the second was ineffective and, most importantly, both methods required the complete cessation of operatihg the building for a long time. In the fact, there was no maneuverable fund for the resettlement of such a large number of people, and there was no possibility to increase rapidly the volume of the factory production and of the new large-panel houses construction. Two years were lost, the earthquake did not occur, which, according to opinion of S.A. Fedotov, increased a probability of destructive seismic event in the coming years.

That is why in 1988, the State Committee for Science and Technology gave a decree to develop the design decisions to improve the seismic resistance of existing multistorey buildings, without stopping the normal operation of such buildings. At the same time, an international competition was announced to find the best foreign methods and technologies to achieve this goal. The Tokyo Declaration of 1988 on Natural Disasters Reduction and then the tragic consequences of the Spitak earthquake in Armenia on 07.12.1988 confirmed the importance of accelerated preparation of Petropavlovsk to the predicted destructive earthquake. More over, the necessity of developing the National Disaster Mitigation Program "Seismoprotection" to ensure the sustainable safety of the most seismo-prone urbanized areas of the country was espesialy underlainded.

2 Organization of work on preparedness to earthquake disaster

Since 1987, all work in compliance with the order of the Council of Ministers of the USSR was under the supervision of the coordination & methodological Council under the leadership of the deputy head of the Kamchatka region. To provide scientific support and the successful solution of the comprehensive to improve the seismic resistance of buildings and to prepare for a predicted earthquake, Gosstroy of the USSR established the Kamchatka branch of the Far Eastern Institute for Construction (KamCenter), which since 1992 has become Federal R&D Center on Earthquake Engineering and Natural Disaster Reduction (CENDR).

The international competition was won by Yugoslavia, which, after negotiations and consideration of proposals from several construction companies, was later represented by the construction company GTT "Adriacoop" (Belgrade). Work on seismic strengthening of buildings was carried out from 1989 to 1999. Then, in 1990, JV "Adriakampacific" (General Director Vojislav Dzogaz) was established.

3 Program approach and initial local engineering basic

The works on seismic strengthening of buildings did not start from scratch; this works were preceded by the significant target R&D and implementation into the practice. Seismomicrozoning map for urban area of Petropavlovsk was refined. In 1986, a program of Preventive Seismic Safety (PRESS) [2, 3] was developed in KamCenter. PRESS consisted of two sub programs: Program for Risk Analysis (PRANA) and Program for Risk Management (PRIMA). In framework of the PRANA, using a developed "Methodical manual on passportization of existing buildings" (K.B. DalNEES, Petropavlovsk-Kamchatsky, 1987), evaluation and certification of the civil and commercial buildings were performed by the end of 1988. The methodology and results of certification were reported at the All-Union Conference "Seismic-resistance of existing structures" (SES-90), approved by the Gosstroy of USSR, presented at 9ECEE (Moscow, 1990) [4] and then widely used in the UNESCO project "RADIUS" for the diagnosis of cities against earthquakes, where Petropavlovsk took part as a city-donor. Some results and local features of the built environment of Petropavlovsk were identified during certification and are listed below:

- structural types of the city's civil buildings are defined; class of structural vulnerability [5] was defined for each type of building; base objects for analysis of safety (BAOBABs) were selected according to next rule – "the same types of buildings in the different soil conditions and different types of buildings in the same soil conditions" [6]; most of BAOBAB were served by the seismic monitoring network;
- buildings have erected in violation of construction code, have not met the requirements of the regularity, and prone to progressive collapse were selected in special list;
- low adhesion of masonry mortar due to the lack of plasticizers (lime) was revealed everywhere; the masonry of hollow stones is not subject to drilling;

- masonry buildings, and then large-block one erected according to seismic standards before 1970, are recognized as the most vulnerable; based on the investigation of the consequences of the earthquake (24.11.1971, M = 7.2) in Petropavlovsk, large-panel residential buildings are recognized as sufficiently seismo-resistant;
- central regional hospital, which was a main object of disaster medicine, consisting of several large buildings, was located at the most hazardous place of city on toxictropic soil prone to dynamic liquefaction under earthquake;
- an address list of the most vulnerable residential houses, children's and medical buildings and live facilities that should be strengthened as a priority has been compiled; for the urbanized area around the Avacha Bay, a priority schedule for seismic strengthening of the most vulnerable buildings, regardless of their ownership, has been determined;
- features of local concrete (γ = 1600-1800 kg/m^3, b20÷b35) based on volcanic slag were carefully studied by Far Eastern Institute for Construction [7]; at the initiative and under the leadership of prof. S.V. Polyakov [8], a test-ground was created in Petropavlovsk for field studies of buildings equipped with various seismic isolation systems, including the device of the "sliding belt" (L. Sh. Kilimnik), "switching off connection" (Ya. M. Eisenberg) and "kinematic foundations" (Yu. D. Chereninsky), which were also considered for seismic strengthening of existing buildings;
- based on the analysis of the seismic hazard scenarios (HASC) set by seismologists, it was concluded that the predicted seismic impact of main shock will be probably of a low-frequency with a long duration (up to 60-80 sec.), in the accompanying the several aftershocks; that is why the increasing of rigidity of buildings was chosen as the main direction of seismic strengthening.

4 New approaches and technologies for seismic strengthening

R&D, calculation and initial design decisions were provided under leadership and due to personal participation of Prof. Boshko Petrovich and Dr. Mark Klyachko in Petropavlovsk. Working projects were performed in the technical bureau in Beograd. The following methods of the seismo-strengthening were proposed and implemented into practice.

4.1 Prestressing wall system (PWS)

Construction type and function of buildings: typical multi storied residential buildings from large concrete block (seria 1-306s); same buildings (seria 1-307s), kindergartens and schools from the prefabricated light-concreted continuous stones; the effective use of PWS is also possible for historical buildings, the facades of which must be preserved in their original form.
Main idea. Increasing the stability of load-bearing walls along the perimeter of the building and its overall seismic resistance; prevention of crack-formation in the masonry.
Special requirements: not exceeding the ultimate strength of concrete stones / masonry under design seismic loading, taking into account the vertical EQ-component.

Description and sequence of operations: the vertical drilling is carried out by means of special equipment; the amount of opening is not less than one for each inter-window partition; the wire cables are pulled through each opening and are anchored in basement and then are tensioned up to design/calculated level; canals are full up by going injection of a special cement compound and then are anchored on the roof.

4.2 Superimposed stiffness (SIS)

Construction type and function of buildings: multi storied residential buildings (including seria 1-307s), kindergartens, schools and hospitals from the prefabricated light-concreted slotted and continuous stones.
Main idea. Such an increase in the rigidity of the outer longitudinal load-bearing walls so that they become strong enough to resist the increased seismic load and the internal longitudinal load-bearing wall does not require additional seismic reinforcement, which is ensured due to the effect of redistribution of the horizontal seismic load between walls.
Special requirements: monolithic floor slabs are preferable to prefabricated ones.
Description. Due to the monolithic concrete works, the creating a continuous or discontinuous rigid RC diaphragm / shell, well connected to the existed wall by steel anchors and using the pre-made openings in the wall, which jointly ensures the required seismic resistance.

4.3 Buttress external double (BED)

Purpose and description. The system of precast or "cast-in-situ" RC buttress erected in the line with the chief lateral walls (especially walls of stairwells weakened by smoke-ventilation channels). This method is successfully used for a seismic strengthening of long buildings with load-bearing walls having the deficient of lateral EQ-resistance.
Special note. Due to the reliable connection of the buttresses to the wall on each floor, additional connection of the double buttresses jointly has not required except for their connection over the roof by a cable tensioned with a force of 2500 kN.

4.4 Dynamic seismic damping (DSD)

Description. Dynamic damping of the seismic impact (DSD) of the 4-5 storeyed residential buildings with both masonry and large concrete blocks walls was performed in two versions:

- superstructure of damping storey ("cold" garret) installed on the seismic-isolating supports (for the version "building with a flat roof");
- by means of the installation of 4 hydraulic dampers of the MHD 215kN type with SIP pendulum supports (manufactured by Maurer Söhne), they are installed on a steel horizontal frame rigidly connected with the prefabricated slabs covered by reinforced concrete screed (for the version of the existing "cold" garret).

Special note. The building must be in operable condition; careful dynamic design of the building and selection of the features of damper should be performed using reliable parameters of the expected seismic impact.
Methods and technologies of seismic strengthening above were approved on the Scientific Board of Gosstroy of Russia under the chairmanship of Prof. S. V. Polyakov in 1991 [2, 9-12]. Passive seismic isolation systems developed by L. Sh. Kilimnik and Ya. M. Aizenberg were not recommended for seismic strengthening of buildings in Kamchatka, at least because of the large number of aftershocks that are typical of the subduction zone; the "kinematic foundations" of Yu. D. Cherepinsky are permissible for use with the addition of dry friction elements, excepting the sites with soft soils.

5 Results and effectiveness of seismic strengthening

The number and volume of strengthened buildings at the 1st stage of the PRESS (until 1996) are shown in table 1. Average population of Petropavlovsk was about 260 000. There was not housing enough, but new construction of large-panel houses compensated for this shortage slowly. Therefore, the second stage of seismic strengthening was very important.

Table 1. Strengthened

	Amount	Signification
Municipal houses	71	173 m^2
Schools and kindergartens	15	3 300 pupils
Hospitals and medical clinics	7	1000 beds

At the 2nd stage of seismic strengthening (1996-1999), the volume of work performed exceeded the previous volume by 10 %, while about 60 % of this volume related to seismic strengthening of multi-apartment residential buildings. At the same time, the method of SIS was used more mainly, because its use not only significantly increased the rigidity of buildings, but also improved their thermal protection and facade finishing. How can we monitor the effectiveness of seismic strengthening?
For assessment of effectiveness of the performed seismic strengthening have used the tool-box [13-17] developed in CENDR, including the mathematical "method of logical estimates and system analysis" (MELOSA), the loss estimation methodology, the disaster magnitude scale (DIMAK) [18, 19] and control disaster scenario (DISCONT). Using the six possible seismic hazard scenarios (HASC), obtained from seismologists, the KamCenter in 1986 developed a computer information retrieval system for risk management [20] and several corresponding probable disaster scenarios (DISC). Later, the improved DISC "ONEGA" was developed together with Yu. Shevchenko from R&D Institute 26, which was used for central part of Petropavlovsk and for town Vilyuchinsk. Due to the DISCONT we have received a good opportunity for numerical simulation of potential

consequences under seismic impact of various intensity, and also we can analyse an effectiveness of both the made and the assumed strengthening [17]. Estimations of the strengthening effectiveness are shown in table 2. Here a night DISC in Petropavlovsk with a macro seismic intensity I = IX was realized.

Table 2. EQ-disaster assessment

Period	EQ-consequences						
	Killed	Injured	Homeless	Total losses ($, mln)	DIMAK Scale scores		
					Md	Terms for disaster description	Score of disaster permissibility
Before PRESS, 1990	3000	14000	100000	8000	5.63	major disaster of national scale	unacceptable
During PRESS, 1st stage, 1995	2000	6000	65000	4200	5.29	major disaster of national scale	unacceptable
During PRESS, 2nd stage,1999	200	1 500	9000	1200	4.29	disaster of territorial scale	semi-acceptable
During PRESS, 3rd stage, 2005	50	200	5000	1000	3.95	disaster of local scale	permissible

Please turn attention, that during the process of increasing the volume and level of seismic strengthening, its effectiveness decreases and there comes moment of "saturation", that is, parameters of the city resilience are not improved. This is due to the peculiarity of the loss estimation methodology, which is based on the real consequences of destructive earthquakes, when a potential number of victims are not directly related to the structural damage degree. In earthquake-prone areas without experience of strong and damaging earthquakes within the framework of MELOSA, instead of or in addition to BAOBABs, similar in design buildings (SIB) should be used, were investigated after damaging earthquakes in other regions of the world; EMS-92, the World Housing Encyclopedia can be used to search for SIBs, but it is better to compile a national catalog of SIBs. New methods and technologies of seismic strengthening and intermediate results of the preparedness in Petropavlovsk for the predicted earthquake were presented at the exhibition during 10ECEE (Vienna, 1994) [21]. In addition to the "RADIUS" project, the above-mentioned tool-box was implemented for risk analysis within the framework of the intergovernmental program "SeismoPolis" to ensure the seismic safety of the capitals and large cities of the CIS countries. In 1996, the Association "Reliability and Safety" together with "Center of extreme situation research" developed on the basis of GIS "Extremum" an improved DISC for Petropavlovsk and the corresponding response scenario (RESC), including the calculation of the necessary forces and means to eliminate the emergency situation [22]. The disadvantage of all DISCs was not taking into account the secondary disaster from the tsunami impact caused by earthquake.

6 Control and testing of strengthened buildings

The verification of seismic strengthening was carried out, first of all, in the course of construction work. Under special supervision were, for example, geodetic control during the implementation of the PWS method or the preparation and placement of concrete mixture, when methods of SIS and BED were realized. The effectiveness of the strengthening of each building was also determined and controlled by measuring the dynamic parameters of natural vibrations before and after the strengthening. The best evidence of the high quality of the work performed was the results of the reconnaissance of several strong earthquakes in 1993, and mainly of the Kronotsky earthquake M = 7.9 on 05.12.1997. Respond of the BAOBABs to these earthquakes was recorded by the seismometric stations installed on them.

7 Conclusions

- The past 35 years have shown that seismologist S. A. Fedotov made a big mistake – a short-term forecast of location, time and intensity of the earthquake simultaneously is not yet possible, but due to this error civil engineers could prepare a large city to destructive earthquake for the first time by the effective preventive seismic strengthening of the key vulnerable buildings.
- The well-tested approaches, methods and technologies of seismic strengthening of civil buildings described in the article, carried out without stopping their normal operation, allow to prevent undesirable consequences (human and monetary losses) of possible earthquakes and to ensure the sustainable safety of urbanized territories, and therefore can be recommended for implementation in Croatia, taking into consideration local conditions and requirements.
- Seismic strengthening must be preceded by the development of a local and national seismic disaster mitigation program such as PRESS, which contains a generalized multidisciplinary approach to improving the community resilience to the design earthquakes. The first event is the survey and certification of the built environment on the earthquake-prone urban areas, in which are appointed the BAOBABs, classes of vulnerability is appointed for each BAOBAB, and the list of vulnerable buildings, which should be strengthened in the priority order, is made.
- The main tool for monitoring of the effectiveness of seismic strengthening are the disaster scenarios (DISC), built on the earthquake hazard scenarios (HASC), given by seismologists; the DISC also permits to develop a research planning, transportation planning, rehabilitation and reconstruction ones, etc.; the acceptable disaster is selected for each urban area by applying the disaster magnitude scale DIMAK, having previously knowledge about an insurance estimate of one victim in the country under consideration.
- In earthquake-prone areas without experience of strong and damaging earthquakes within the framework of MELOSA, instead of or in addition to BAOBABs, similar in

design buildings (SIB) should be used, were investigated after damaging earthquakes in other regions of the world.
- Under the normal conditions of a long-term seismic prognosis, the construction of new modern housing stock instead the old worn-out houses is the best solutions, but this way to improve urban sustainability to earthquakes is very depends on the economic potential of the state and the population; therefore, the balance between the volume of new comfortable housing stock and modern public buildings, from one side, and the quantity of seismo-strengthened existing buildings, from other side, is determined due to the feasibility study and becomes one of the basic provisions of the national program of the PRESS type.
- In some cases, for seismic strengthening of existing buildings-monuments, objects of historical and cultural heritage the modern methods of seismic isolation and damping (passive or even active) are recommended to use; in this case, soft soils in the base of the building are, as a rule, the only restriction for the use of seismic insulation.
- The authors are ready and will be happy to share with their colleagues knowledge and experience in preparing seismo-prone urban areas as whole for predicted earthquakes and, in particular, in the field of increasing the seismic resistance of existing buildings.

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