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Article

Evaluation of the response of historical structures fitted with seismic-isolation

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Abstract: The paper highlights the performance of the seismic isolation devices installed on retrofitted buildings in reducing the seismic response when subjected to earthquakes. Two buildings from the beginning of the XXth century in Bucharest are chosen from many more, monitored over the city area. We discuss the response of these base-seismic isolated structures, relying on good quality data acquired from the recent strong earthquake (3 November 2022, $M_W = 5.0$). Elastic response spectra computed from recordings at two levels of each structure are used, placed under and right above the isolating layer. At one building, the existence of previous recordings and the particularity of the sensors allow a comparison with the other two relatively recent medium-intensity earthquakes. The assessment is carried out in terms of maximum acceleration a_{max}, measured at certain levels in each structure, spectral acceleration amplitude SA_{max}, and spectral-peak corresponding period. We find that the base-isolation methodology is effective in reducing the response of the building right above the isolating layer, an observation valid for both structures, all components of the recordings, and spectral acceleration values. Moreover, the outcomes from the modal evaluation performed prior to rehabilitation and the seismic isolation process are presented by pointing out a higher newly acquired fundamental period of the isolated structures.

Keywords: historical retrofitted buildings; seismic isolation performance; spectral parameters; Vrancea earthquakes; medium intensity seismic activity

1. Introduction

The instrumented buildings performance over the Bucharest area has already become a continuously undergoing task with valuable results [1–3]. The level of performance enhancement and the state of damage for a large variety of structures were assessed in terms of years and type of construction, design, usage destination, and utility [4–7]. Detailed structural response data provide a potential for adjustments in the design process. The present study is focused on two old, seismically base-isolated buildings and retrofitted buildings located in the Bucharest city area. The selected buildings erected at the beginning of the XXth century are hosting administrative and educational activities.

The dynamic behavior during the earthquake of 3 November 2022, $M_W = 5$ [8] is analyzed. This is a continuation of a previous work, where the impact analysis of the methodology used for near-real-time response was carried out [9]. The monitoring system has proved its capabilities to ensure the data flow and make them available in a shorter time after the earthquake to the authorities, civil protection, decision makers, etc. Basically, near-real-time (i.e., right after a potentially damaging event and/or during its aftershock sequence) structure response-based status was assessed. The novelty herein consists in an evaluation of the response of a previously seismically isolated building, now endowed with new sensors located above/under the isolating layer. A comparison is made with other old buildings' responses, already having the same type of deployment for the isolated device and sensors. The responses under another two recent earthquakes are brought into attention for the same structures, and a discussion is made from the recorded parameters and spectral-related characteristics perspective (maximum acceleration $a_{\max}$ considered at certain levels in each structure, spectral acceleration amplitude $SA_{\max}$, spectral-peak corresponding period [3]).

2. Methodology, procedure, and building characteristics

Isolation devices are capable of sustaining dynamic strength at strong displacements induced by the ground motions. The soil particularity consisting of soft, weak-consolidated, without cohesiveness mechanical characteristics, usually included in sedimentary layering or basins, can be an issue in building design. Nonlinear phenomena in these cases add weight to the general dynamic behavior. The difficulties that have to be surpassed consist in different amplification at the ground level, a high oscillating site period, or strong variability of the involved parameters over the interest area. Therefore, a thorough seismic hazard, correct site response, and geotechnical information knowledge are compulsory for these zones. As regard the concept of isolation procedure, it must raise the flexibility and damping and withstand service loads.

The undesired response of the structures may be avoided by taking necessary measures in terms of design, as emerged from a thorough understanding of the seismicity and ground motion characteristics. The seismic isolating devices can be used in order to reduce the structure vulnerability. In this regard, among the techniques largely used in some countries, the base isolating method has been proved successful (USA, Japan, Italy, and New Zealand) in relation to the seismicity specificity and geophysical and geological characteristics of the interest areas [10–19]. In general practice of seismic isolation, the main aim is to reduce the seismic demand on the structure. The buildings considered in this study were endowed with the above-mentioned base-isolating systems. The isolation system does not absorb the earthquake energy, which is deflected through the dynamics of the system. The technique involves a certain level of damping that is helpful to avoid possible resonance. By decoupling a structure from the direct action of the horizontal components of a ground motion, it acquires a fundamental frequency that is much lower than its fixed-base frequency and the usual predominant frequencies of the ground motion. Based on the modal evaluation of the fundamental vibration period, an insight into the benefits of using base isolators in structures could be gained by considering the special case of a two degrees of freedom structure, which is separated from the ground by some type of isolating device [20–22]. The study relies either on a single degree of freedom model, with possible nonlinearities included, or, more exactly, on a system of coupled elastic oscillators [23–28].

Some buildings host costly equipment and contents that must be protected against earthquakes and be operational after a severe ground shaking; such buildings are those designated for research, health care, telecommunication, nuclear power plants, etc. Buildings constructed by following old seismic codes with conventional resistant design approaches cannot protect the people or the valuable equipment that is contained. The constructions evaluated in this study were not randomly chosen, but taking into account their age, importance, and design. One of the chosen buildings is an administrative one, hosting the Bucharest City Hall (BCH), the other being the "Victor Slavescu" building, belonging to Bucharest University of Economic Studies (ES). For both, the isolating devices were implemented at certain elevation points in the basement, according to the design and retrofitting specifications (**Table 1**). By this procedure, the suprastructure was decoupled to some extent from its foundation, which continues to move rigidly with the soil during an earthquake.

Table 1. Seismic isolated buildings (general characteristics) [5].

No.	Name of building/monitored period	No. of floors	Year of construction	Structural system
1	General City Hall of Bucharest (BCH)/ 2017–2021, 2022-present	B + GF + 3F + Attic	1906. The building was consolidated after 2010 and was equipped with seismic insulators in the basement	Brick masonry with reinforced concrete floors with turned caissons
2	"Victor Slavescu" Building, Academy of Economic Sciences (ES) 2011-present	B + GF + 2F + Attic	1905, retrofitted in 2009, 2011 (added seismic isolators)	Brick masonry with truss roof

Legend: B–Basement; GF–Ground Floor; F–Floor.

For the modeling of the isolating system of the BCH building, some types of constitutive laws were used, such as those characterizing a linear elastic or biaxial-hysteretic behavior [29]. The preliminary analysis of the isolated building involved dynamic linear and non-linear computation of time-history type. A direct integration of the differential equations of motion based on recorded accelerograms for the 1977, 1986, and 1990 strong earthquakes was employed, imposing the input condition of 0.24 g for the scaled maximum acceleration at the ground level. The data were taken at a location that is the only one where recordings for the 1977 earthquake exist; also, it has the advantage of similar local soil features. The results show a reduction of 11–12 times for the relative displacement values on one horizontal direction and 7–8 times on another, of the seismic action at a vibration period of the isolated building of 3.3 s. As regards the stress reduction, the values are 4 and 3 times smaller for the two horizontal seismic action directions. At the same time, the relative displacements distribution at the level of each floor on the vertical shows a general solid-rigid trend of displacement, with a general displacement at isolated interface level of approximately 20–22 cm and 28–30 cm for horizontal directions of the seismic action, under the assumption of peak ground acceleration of 0.24 g, according to P100-1/2006, which was the code in force at that time [29,30].

For the ES building, the preliminary study [31] employed the same computation program (ETABS NON-LINEAR v.8.4.5.), relying on the finite element method. Modal analysis for the resistance structure has considered the first six vibration modes, as follows: three of one horizontal translational direction, two of the other horizontal direction (perpendicular to the former), and one of general torsion. All these vibration periods are in the 0.08–0.79 s range. Following the reduction of stress and displacement values, stress values diminished by 2.4 and 2.5 times for two horizontal seismic action directions, and relative displacements reduced by 3.5 at story levels and 2.5 at ground level, respectively, for both horizontal seismic action directions. The vibration period of the isolated structure was 2.8 s. At the same time, the relative displacement distribution at each level on the vertical shows a general solid-rigid trend of displacement, with a general displacement at the isolated interface level of approximately 15 cm and 20 cm for the horizontal directions of the seismic action [31].

The comparison was made to the performance of the two buildings using the same analyses carried out by employing specific design parameters without taking into account the isolation device characteristics.

The BCH building was seismically monitored with 4 sensors located on the isolated structure from the year 2017; starting with the year 2022, one sensor was deployed above/under the isolator layer. The ES building is permanently monitored by the National Institute for Earth's Physics (NIFP) from the year 2011, with seismic accelerometers at two different levels (status at 31 December 2022) [32].

The characteristics of the most recent considered earthquake were as follows: date and triggered time 3 November 2022, 06:50:25, local time, lat. 45.4895° N, long. 26.5262° E, focal depth 148.8 km, M_W = 4.9, ROMPLUS Catalogue, 2023 [33], 122 km epicentre distance for Bucharest, and M_W = 5 according to the near-real time release of the Internal Report [8]. Herein, a magnitude 5 is considered; as for the other two earthquakes, the values in ROMPLUS are identical to those in the internal reports released in the very short aftermath of the recordings [33–35]. Moreover, the data processing and computation of the parameters are based on the mentioned references, according to the purpose of the work that involved a near-real-time evaluation of the response.

The earthquake mentioned above belongs to the intermediate-depth Vrancea seismic region and was felt with intensities about V on the MSK scale in the epicentre area and III-IV in Bucharest. For the other two seismic events, the characteristics are: date and triggered time: 28 October 2018, 03:38:11 local time, lat. 45.6079°, long. 26.4068°, focal depth 148 km, M_W = 5.5, and 31 January 2020, 04:26:48 local time, lat. 45.6937°, long. 26.6918°, focal depth 118 km, M_W = 4.8 (**Table 2**) [33]. The intensity on the Mercalli scale was VI and IV, respectively, in the epicentre zone [34,35].

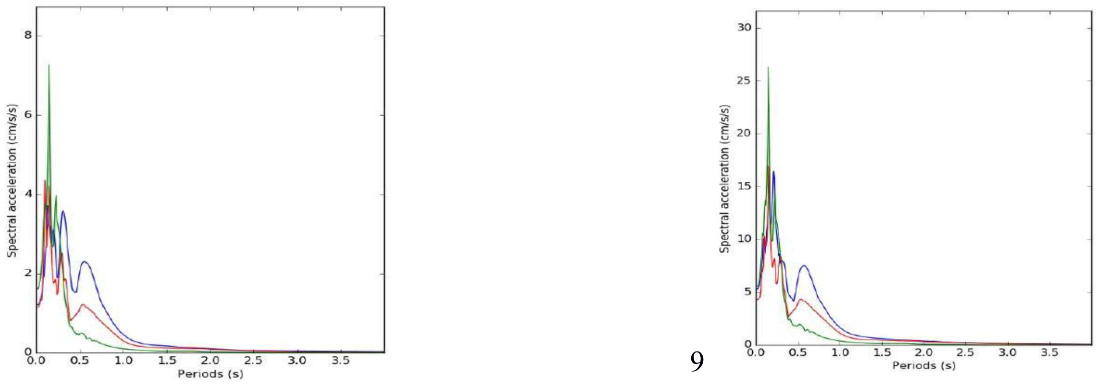
Table 2. The characteristics of the three considered earthquakes [33].

Date	Time [UTC]	Depth [km]	M_W
28 October 2018	00:38:11	148	5.5
31 January 2020	01:26:47	118	4.8
3 November 2022	03:50:25	148.8	5.0

3. Response analysis

The instrumental data from the two selected structures, subjected to a medium-intensity earthquake, were processed in terms of peak recorded accelerations and spectral accelerations at two levels, below and right above the isolating devices. Recordings from three-component accelerometers, installed on these levels, consisting of acceleration time histories are pre-processed: baseline corrected and filtered using a 4th order Butterworth bandpass (0.2–25 Hz) filter. The limits were set for obtaining a good signal-to-noise ratio, and also a taper function was applied to the data to allow the spectral-related calculation. The sensors are of the same types, and the recordings and data processing are performed according to the standard procedure by the automated Antelope seismological system, developed by Boulder Real Time Technologies [36] and installed at the National Data Centre (NDC) of the National Institute for Earth's Physics [32]. It includes program applications and module units that are run in order to ensure data acquisition, automatic seismic event detection, location, magnitudes, and other parameters computation or evaluation. The ground shaking and building seismic response parameters processing (in terms of peak ground acceleration, maximum buildings recorded acceleration, spectral acceleration, and related fundamental or oscillation period) are the tasks that are accomplished through this system.

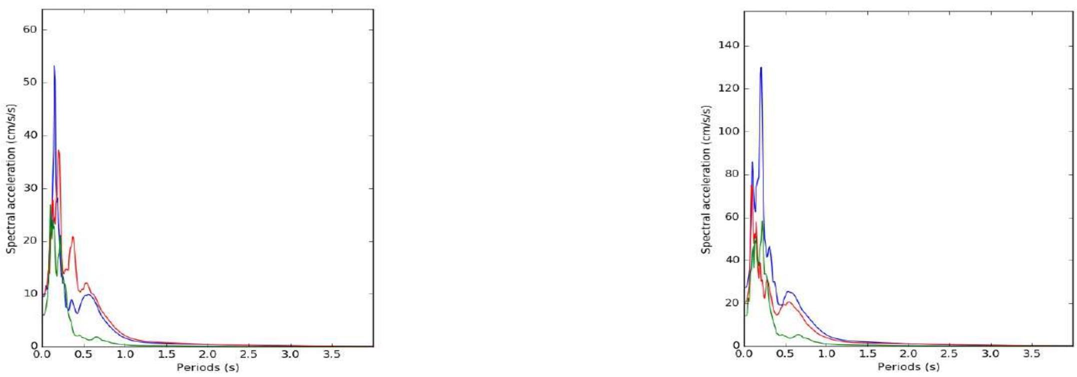
The processing of the data releases elastic response spectra in terms of spectral pseudo-acceleration with 5% damping (**Figures 1** and **2**). The information is depicted as engineering parameters, that are maximum acceleration a_{max} recorded on three directions (two horizontal, NS, EW, and one vertical Z), maximum spectral acceleration (SA_{max}) from elastic response spectra, and corresponding oscillation periods T_{SAmax} (**Tables 3** and **4**).



(a) **(b)**

Figure 1. Elastic response spectra for the BCH building above **(a)** and under **(b)** isolating layer from recordings of the 3 November 2022 earthquake M_W= 5 [9].

Legend: red: N-S, blue: E-W, green: Z (vertical) components of recording.



(a) **(b)**

Figure 2. Elastic response spectra for the ES building above **(a)** and under **(b)** isolating layer from recordings of the 3 November 2022 earthquake M_W= 5 [9].

Legend: red: N-S, blue: E-W, green: Z (vertical) components of recording.

Table 3. Base-isolation performance at BCH and ES buildings for 3 November 2022, M_W = 5.0 earthquake [9].

Date/ Magnitude M_W/ Depth	Station		Component								
			N-S			E-W			Z		
			a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)	a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)	a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)
3 November 2022 M_W = 5, 148.8 km	ES	Above	9.83	37.29	0.2	9.48	53.24	0.15	6.04	26.85	0.1
		Under	20.59	74.95	0.09	27.45	130.08	0.21	14.25	58.28	0.22
	BCH	Above	1.16	4.35	0.1	1.21	3.72	0.13	1.62	7.28	0.15
		Under	4.32	16.95	0.15	5.33	16.45	0.21	5.54	26.36	0.15

Table 4. Response spectra parameters at the ES building for three seismic events (M_W = 5.5, 5.0, 4.8).

Station ES	Earthquake	Component								
		N-S			E-W			Z		
		a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)	a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)	a_{max} (cm/s²)	SA_{max} (cm/s²)	T_{SAmax} (s)
under	28 October 2018 M_W = 5.5	131.77	347.53	0.14	100.42	416.61	0.15	50.64	228.89	0.13
above		34.04	108.28	0.16	47.39	196.25	0.16	25.7	133.19	0.12
under	3 November 2022 M_W = 5.0	20.59	74.95	0.09	27.45	130.08	0.21	14.25	58.28	0.22
above		9.83	37.29	0.2	9.48	53.24	0.15	6.04	26.85	0.1
under	31 January 2020 M_W = 4.8	11.69	36.02	0.08	13.34	43.81	0.31	6.24	26.49	0.11
above		5.75	18.42	0.42	5.86	23.43	0.34	4.57	22.27	0.11

In **Table 3**, a clear decrease of the peak acceleration recorded by the seismic sensors above the isolating device can be seen. This is valid for all components of the recordings and at both buildings. Also, the maximum spectral accelerations, as shown in **Figures 1** and **2** and **Table 3**, display lower values above the isolator. The corresponding oscillation periods are all in a low and narrow range of 0.09–0.22 s, excluding the danger of possible resonance effects. Another observation is higher values for recordings at the ES building in comparison with the other building (BCH) at both instrumented levels. We note that this phenomenon is encountered at the ES building for other earthquakes of comparable magnitude in comparison to any other instrumented structure in Bucharest city area (**Table 4**) [2,3]. The higher recorded values at the ES building for low and medium magnitudes can be a matter of local soil conditions or due to the building dynamic characteristics themselves.

Moreover, at this building more data of good quality are available, both under and above the isolating layer; therefore, one can infer the dependence to the earthquake magnitude. From **Table 4,** it may be seen the increase of the recorded values with the earthquake's source level of strength for all measured and processed parameters.

We can also note the higher values of the oscillation period corresponding to spectral amplitude (**Figures 1** and **2**, **Table 4**) for the 31 January 2020, M_W = 4.8 earthquake, which is the lower magnitude considered in this study. These higher values are encountered for horizontal components and above the isolated layer. The other values (i.e., under isolation and both for the vertical Z component) follow the general tendency of laying in a rather low and confined range, as it is expected for these types of earthquakes. It is worth the focal depth range of ~122–149 km for these three earthquakes, besides sharing the same focal area (Vrancea-intermediate depth) and moderate magnitude (**Table 2**).

In **Table 5**, the reduction of the seismic amplitudes is shown in terms of maximum recorded accelerations in order to have a quantitative representation for the outcome of the employed technique. For this purpose, the ES building is considered, for which more recordings exist with this type of isolating device. It is the first building to benefit from this technique and a proper sensor deployment, allowing for this type of analysis. All three earthquakes are of medium magnitude, originating in the same focal area. The reduction coefficient represents the ratio for under/above values, and the reduction percentage stands for its corresponding percent in the weight reduction. As it may be seen, the average for three relatively recent seismic events is over 50% on the two horizontal components and below this value for vertical ones. The maximum average reduction is attained for the N-S component, with 59% the higher value, corresponding to the strongest earthquake (74%, M_W = 5.5).

Table 5. Base-isolated device performance in terms of reduction coefficient and corresponding reduction percentage for the ES building for three seismic events.

Building ES, earthquake/magnitude	Component N-S		Component E-W		Component Z	
	Reduction coefficient	Reduction percentage	Reduction coefficient	Reduction percentage	Reduction coefficient	Reduction percentage
28 October 2018 M_W = 5.5	3.87	74%	2.11	52.8%	1.97	41.8%
3 November 2022 M_W = 5.0	2.09	52%	2.89	65.5%	2.35	57.9%
31 January 2020 M_W=4.8	2.03	51%	2.27	56%	1.37	26.7%
Average	2.66	59.0%	2.42	58.1%	1.89	42.13%

The consequence of the base-isolating procedure consists in raising the fundamental period for the supra-structure, or the shift of the base-supra-structure ensemble, and splitting in two values if they are considered as two coupled oscillators [23,37,38]. In some cases, this increase is considered a goal itself. However, the benefits of this outcome and its limits of applicability are discussed in correlation to various types of parameters, from the source characteristics to local effects and specific soil responses [5,37]. The structure design and dynamic features are also taken into consideration [6,7,18,19,39,40].

According to Iordachescu and Iordachescu [29], Marmureanu et al. [31] previous studies a shift towards 2.5–3 s for fundamental periods can be obtained. Given the oscillation periods of the strong and damaging earthquakes that hit Bucharest of over ~1 s, but not exceeding 1.6 s (until now!) [41–44], it can be stated that the technique has accomplished this particular point. According to the current Romanian seismic design code P100-1/2013 [45], three values of the control period T_c = 0.7, 1.0, and 1.6 s are considered in the design response spectra provided by this regulation regarding the whole Romanian territory. In this respect, for Bucharest city, a control period of T_c = 1.6 s and 0.3 g as the value for the design ground acceleration is recommended.

At the same time, the values for the soil predominant periods accepted for the city area [46,47] are in the 0.7–1.9 s domain [48]. In particular, values between 0.08–

0.79 s for the first six normal modes of vibration are suggested. It follows that the value of ~2.8 s for the ES building fulfills the objective of extracting the structure from the dangerous range of maximum amplitude of the response spectral at that site [29,31].

From **Table 4**, one may see the lower range for this parameter (oscillation period for the maximum spectral amplitude) at both buildings for all components (0.09–0.42 s). Among them, the higher values correspond to the ES building and are encountered for the less strong earthquake of 31 January 2020, for the horizontal components.

Turning back to the BCH structure, one may notice as specificity the higher values on vertical component Z in terms of maximum acceleration and spectral acceleration, in comparison with the horizontal ones, as long as, usually for this component (Z), the values are the lowest at both buildings. This situation corresponds to the two strongest earthquakes discussed here (3 November 2022, M_W = 5.0 and 28 October 2018, M_W = 5.5).

4. Discussion

During the last decade, certain types of structures were selected, according to their specificity (old buildings, retrofitted, destination and functionality, etc.), and continuously seismic monitored. Several instrumented buildings from Bucharest city and one from the epicentre area (city of Focsani, Vrancea region) have provided important data about the seismic performance of earthquake protection systems and checked out the performance goals and design issues in major earthquakes [3,6]. Out of them, two buildings, Bucharest City Hall (BCH) and "Victor Slavescu" (ES), were constructed at the beginning of the XXth century under inappropriate seismic design regulations. These structures, together with another one, a historical monument (the Arch of Triumph), have been retrofitted in order to endure the future strong earthquakes. Thereafter, the decision was taken for these buildings to be equipped with base-isolating systems (seismic isolators and viscous dampers) for reducing the lateral forces induced by strong seismic movement. One of them (BCH) has been recently endowed with a pair of seismic sensors at the basement level, above/under the isolating system. The response of the two buildings BCH and ES, subjected to medium-intensity earthquakes, was analyzed in terms of peak accelerations and spectral accelerations. Improvement in seismic response of these isolated buildings in Bucharest was evaluated.

5. Conclusions

According to our analysis, the main objective of the base isolating system is considered accomplished, as the efficiency of this type of isolation device during Vrancea-intermediate depth-originating earthquakes was proved.

The methodology has proved its aim to reduce the response of the building right above the isolating layer in comparison with values under the device. The observation is valid for both structures, all components of the recordings, and for the spectral acceleration values.

These results can be useful for quantifying the benefits and implications of seismic isolation subjected to moderate seismic events that occur in the Vrancea seismic region in terms of response spectra analysis.

The seismic monitoring of buildings has proved its capability to give a rapid damage assessment after a strong seismic event, based on the level of accelerations the buildings experienced, therefore mitigating the seismic risk for densely populated areas in Romania. Detailed structural response data provide the potential for adjustments to the design process. For the earthquake protection systems, as is the seismic base isolation case, the improvements in terms of structural response can be quantified, and the performance of the isolator devices can be assessed based on measured data.

For the specific situation of Bucharest city, including geology and corresponding site effects, the dynamic parameters must be assessed accordingly in order to estimate the proper seismic response.

The goal pursued was to take advantage of this performance while proving the potential benefits of this certain type of anti-seismic isolating technique applied to old/historical structures located in the Bucharest city downtown. The practical implications of the findings pertain to seismic risk management for this highly populated zone.

Evaluating the performance of the base-isolating technique through comparing the responses under and right above isolating devices may be useful for implementing this procedure on other structures sharing the same similarities in terms of age or design.

Data from this paper could help future practitioners and policymakers decide if using a seismic isolation system for a certain building could mitigate its vulnerability to earthquakes.

Local amplification effects and site effects are important as they determine seismic ground motion specificity and dynamic building behavior ultimately. Therefore, these retrofitting techniques should be considered and recommended for certain urban areas in tight connection to regional seismicity and seismic source specificity, considering typical seismic structural response and local effects-related parameters.

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