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Investigation and Analysis of Empirical Field Seismic Damage to Bottom Frame Seismic Wall Masonry Structure

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ABSTRACT

To understand the seismic damage characteristics of bottom frame-wall buildings and to study their seismic performance, the seismic damage outcomes of bottom frame-wall structures in Du jiang weir by the Wen chuan earthquake on May 12,2008, China were field observed and studied. The assesment of the seismic damage to the bottom frame-wall masonry in Du jiang weir urban showed that the damage to the type of structure system was serious and including damage to the bottom frame, the bottom storey, the transition storey, the bottom node and the rear longitudinal wall, combining with the failure characteristics, the failure reasons and mechanism were analyzed and the corresponding treatment measurements are given. However, a substantial number of bottom frame seismic wall masonry structures (BFSWMSs) after 2000 are basically undamaged. The field inspections team sampled 2178 buildings of the urban ensemble observation. A considerable number of buildings seismic fortified have shown excellent seismic performance in Wenchuan earthquake, which sufficient illustrates the significant role of seismic fortification factors in structural design. Through, the investigation and analysis of its empirical seismic damage, the main measures to improve its seismic performance of construction structure. The above analysis results can provide a reference for seismic design and the revision of seismic intensity scales.

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1. INTRODUCTION

The Wenchuan M8.0 earthquake on May 12, 2008, China, was one of the most serious earthquake disasters in China since the founding of the People's Republic of China. It is a highly destructive and wide-ranging earthquake. Seismic disasters are among the typical disasters that cause the collapse and destruction of a substantial number of buildings and other engineering structures as well as casualties. The masonry structure, reinforced concrete structure, brick and wood structure , and bottom frame seismic wall masonry structure (BFSWM) have been subjected to severly earthquake damage. Among them, in a proportion of developed and developing countries, shops, restaurants or banks are located on the bottom storey or two storeys of settlement and office buildings facing the street. The frame-aseismic wall structure is adopted in the bottom or the bottom two stories of the building ,due to the spacious space required for the use of functions, setting up a certain number of seismic walls along the vertical and horizontal direction. The upper floors are normally residential buildings, using masonry walls with more vertical and horizontal walls as load-bearing system, which is the bottom frame-seismic wall masonry buildings (BFSWMS). Such masonry wall has been evaluated by Jia et al. [1] based on the investigative results of seismic damage to buildings in Du jiang weir city; the spatial distribution and causes of seismic damage to buildings were studied. It is noted that spatial evolution is the main factor affecting the spatial distribution of seismic damage. Before 1980s, the mean damage index of buildings was up to 6.5 times that of new buildings. The failures in the proportions of the frame, BFSWMS and construction quality were compared and summarized. In addition, other structural types were considered. The general law between damage

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grade and failure ratio for multiple construction years was also summarized. Based on the failure characteristics of different structural types occurring in typical seismic environments, the seismic damage to BFSWMS in multiple construction years is analysed. It is proposed that the stiffness ratio of the bottom frame to upper masonry structure should be reasonably controlled [2]. The seismic joint, vertical stiffness, uneven strength and joint failure in reinforced concrete structures were analysed, and safety measures are given in literature [3]. The seismic damage investigation of a multi-storey masonry structure is performed, and the main cause of the damage is found to be the insufficient bearing capacity of the wall between windows [4]. Typical cases are selected in the seismic damage investigation. In the field observation of seismic damage, typical cases are selected to analyse engineering geology, building structure, lifeline engineering seismic damage and so on; the seismic measurements used in ancient buildings in earthquake-stricken zones should be reasonably considered, and the use of timber structures and seismic isolation and shock absorption technology should be promoted [5, 6, 7]. In abundant seismic damage field investigations and inspection, the typical damaged buildings of frame structure, brick structure, BFSWMS, timber structure and steel structure are investigated and analysed, and some solutions and measurements that are of great significance to the empirical seismic damage situation are given. However, most of relatively research focusing on sampling and analysis within comprehensive seismic damage investigations in a fortified intensity zone. To perform a more comprehensive and systematic in-depth study of the seismic damage of BFSWMS in a specific seismic zone, this paper analyses the results of a comprehensive seismic damage investigation of BFSWMS in a location zone and takes advantage of intensity scale to assess the empirical seismic damage grade and to analyse the structural damage index; these analyses are considered in combination with mutiple intensity zones with a goal of evaluating a given seismic zone more accurately. The evaluation of the empirical seismic damage situation of the type of structure provides reference suggestions for the future of both seismic design and the revision of the seismic intensity scales for BFSWMS.

2. BRIEF INTRODUCTION TO STRUCTURAL SEISMICS IN DU JIANG WEIR CITY

In July 2008, China Earthquake Administration organized experts conducted in-situ seismic damage investigation of buildings in Du jiang weir urban during the Wenchuan earthquake in conjunction with the Chinese Seismic Intensity Scale (GB/T17742-1999, CSIS99); where is 21 km from the epicentre of the 2008 Wen chuan Earthquake and was seriously damaged during this event. The city belongs to a near-field strong earthquake urban within the entirety seismic zone; which spans intensity VII-XI regions. Buildings in the city with multiple structures can be roughly split into three categories [11], as summarized in Table 1.

Type A buildings are mostly old and self-built brick and adobe construction without seismic fortification [5, 6]. Starting with the typical failure characteristics of seismic damage, a comparatively in-depth study has been carried out. Type B buildings are mostly brick masonry structures and BFSWMS built without considering or improving seismic requirements. Lei et al. [8] analyses the reasons why the masonry structures built in earlier years mostly adopt prefabricated slab assembly storeys and fail to reasonably consider the seismic requirements, bringing about massive structural failure. Type C buildings are mostly aseismic buildings. The typical seismic damage phenomena and characteristics of reinforced concrete frame structures are summarized and analysed in literature [3, 10]. The field investigative results of seismic failure to timberworks are analysed, and the main characteristics of seismic damage are given in literature [7]. It is proposed that seismic isolation and shock absorption technology should be popularized in the design of timber structures to improve their seismic performance. The seismic damage investigative data on multi-storey masonry structures are organized and summarized, and the causes of diversiform damage phenomena are comprehensively analysed [4]. Li, et al. [2], Rosti, et al. [5], Eleftheriadou and Karabinis [9] have investigated the seismic damage of masonry buildings with BFSWMS. Taking some typical damaged buildings as an example, the relationship between the location of weak floors and the failure state was analysed. The seismic damage characteristics of "standard bottom frame" and "mixed bottom frame" are summarized. It is noted that the structural system should be set reasonably, and the shear and bending resistance of transition storeys should be strengthened. Relevant conclusions are found, such as the need to match the seismic capacity of the bottom and upper regions of brick buildings. According to the investigation, BFSWMS is widespread used and has abundant information. Most of the bottom or bottom two-storey frames are adopted to improve their use function. The bottom stress system is a frame structure; the upper structure is brick masonry structure for residential use, and its stress system is a vertical and horizontal wall load-bearing structure. The type of structure is still used in particular situations. Therefore, it is necessary to research the seismic performance of BFSWMSs. Most of the studies on BFSWMS focussed on the damage to a typical building, which fails to reflect the general nature of the damage. Therefore, it is necessary to conduct a comprehensive investigation and study on the seismic damage to this type of structure in a location region. The BFSWMS of Du jiang weir city

TABLE 1. Classification of structures in Du Jang weir city

A	B	C
Old unreinforced brick masonry or adobe construction and resident self-built buildings without seismic fortification	BFSWMS and brick-concrete masonry structure without considering or perfecting seismic fortification	Seismic design masonry structure, timberwork, BFSWMS and reinforced concrete frame structure

were failured to multiple degrees by the Wen chuan earthquake. Most of the buildings that were designed and constructed according to the code for seismic design of buildings (GBJ11-89, China) without seismic walls. Most of these buildings had mainly horizontal walls and vertical walls. To meet the commercial requirements, a handful number of vertical walls were installed along the axis of the street. In the code for seismic design of buildings (GB50011-2001,China), seismic structural measures for BFSWMS are strictly stipulated, including the corresponding relationship between integrality storeys and intensity, the setting of structural columns at the corresponding positions of transition storeys at the bottom frame columns, the use of cast-in-situ reinforced concrete slabs at the bottom of transition storeys or reliable bonding with cast-in-situ storey slabs, and the rigidity ratio between the bottom storeys and transition storeys.

In developing countries and proportion developed countries around the world, BFSWMS is extensive used, mostly existed in residential urban areas. This paper investigates and analyses the seismic damage of 2178 BFSWMSs in Du jiang weir city. The inspection team conducts meticulous investigations one by one in accordance with the code for seismic design of buildings (GB50011-2001) and CSIS99. It is found that most of the buildings designed after 2000 are basically intact. In 1980s, and 1990s, BFSWMS, which were not designed and constructed in accordance with the seismic code, suffered from multiple degrees of diffused damage. In addition to damage to the bottom frame joints, column footings, transition storeys and other storeys and cross-oblique cracks in BFSWMSs, a plentiful number of which have sustained apparent damage to the rear longitudinal wall and, even under the condition that the bottom frame and transverse wall are basically intact, the phenomenon of the collapse of the rear longitudinal wall; the displacement of additional columns at the top is serious, as this causes the local collapse of the rear elevation.

3. INVESTIGATION AND ANALYSIS OF SEISMIC DAMAGE OF BFSWMS IN DU JIANG WEIR CITY

3. 1. Serious Damage to the Bottom Frame Story

The lateral stiffness of the bottom frame is much lower than that of the upper masonry structure due to the absence of or a minority number of anti-seismic walls. The inter-story displacement of the bottom floor is more prominent under seismic influence, which consequences in the phenomenon of concentrated deformation of the bottom floor. The shear bearing capacity is relatively lower, and the bottom floor is a weak story under strong vibration effect. Because of the stiffness remarkable discrepancy between a precast story slab and column and beam, the integrality storey slab collapses, as shown in Figure 1, due to the apparent anomalies of the lateral resistance structure system between the bottom and the upper storey, for the sake of assurance floor has the stiffness to transmit horizontal seismic force, the code for seismic design of buildings (GBJ11-89, GB50011-2001, China) strictly requires that the bottom roof be set as cast-in-place reinforced concrete slab. However, a protion structures adopt prefabricated floor slabs and have weak anchorage connections with beams and columns. Failure of floor slab due to design and construction not strictly in conformity with building seismic code. The seismic design code explicitly stipulates that the stiffness ratio of the transition to bottom story should less than or equal to 2.5 in the VII intensity zone， guarantee the average strength coordination between storeys. However, in the field observation of seismic damage, the lateral stiffness ratio of transition to bottom story of partially structures is not less than 6, and no or only a spot number of seismic walls, which makes the shear bearing capacity of the bottom grievous deficiency, and the bottom becomes weak story under strong vibration. The lateral displacement apparent anomalies of partial structures when the seismic wall is not reasonably installed at the bottom, as shown in Figure 2. It is found that the strength and stiffness of part of the bottom frame layer are lower than those of the upper masonry structure, resulting in the overall collapse of the bottom layer, as shown in Figure 3. To enhance the lateral stiffness of the bottom story, adequate increase of seismic wall, and the stiffness requirements between the bottom frame and the upper masonry should be rigorously controlled in accordance with the seismic code to enhance the ensemble deformation coordination of the main structural components.

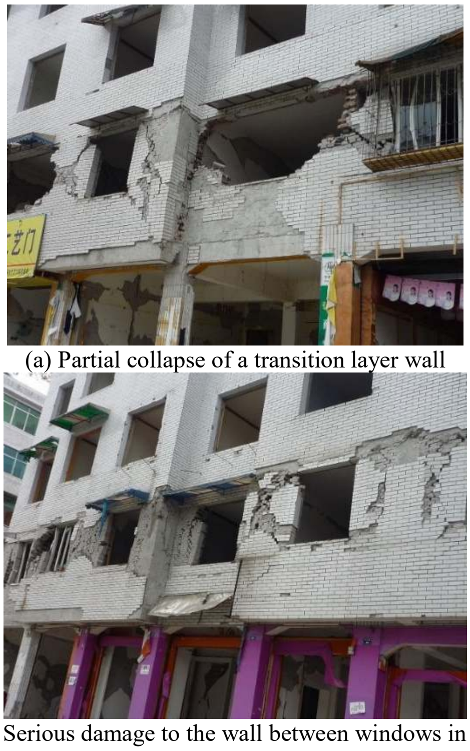
Figure 1. Serious collapse of a bottom frame story

Figure 2. The bottom frame lateral displacement enlargement

Figure 3. The overall collapse of the bottom layer

3. 2. Serious Damage to the Transition Story The transition story in the BFSWMS is normally the first story of the upper masonry structure of the bottom frame. The stress and transmission of the transition layer at the junction of the bottom frame and masonry structure are inconsistent. Due to the underlying set of seismic walls, the bottom stiffness is increased compared to structures without aseismic walls on the ground story. Failure to install aseismic walls on the bottom story as required by the aseismic code, because of the requirement for include a bottom partition and for maintenance purposes, partially filled walls have been established, which contribute, to a certain extent, to seismic resistance. The weak layer of the structure moves upward, and the damage to the transition layer is more remarkable than that of other layers. The building seismic code (GB50011-2001) strictly stipulates that when the length of the transition layer wall exceeds 5m, reinforced concrete structural columns shall be added to the wall, avert detrimental behavior of short columns, and strengthen its seismic capacity. However, according to the empirical field seismic damage inspections, The transition story of a portion of the structure fails to comply with the provisions of the seismic design code, which causes serious failure of the story. As indicated in Figure 4a, the transition story experienced serious destruction, and the bottom frame was lightly damaged even under the action of reciprocating horizontal earthquakes parallel to the wall direction. The characteristics of seismic damage are noted as basically intact, slightly damaged and moderately damaged. As shown in Figure 4b, shear-type one-way or "X" cross-oblique cracks appear in the seismic wall. Although the bottom seismic wall is damaged to a certain extent, the subject frame can still continue to work. However, the stiffness of the transition story is relatively weaker, resulting in serious shear failure of the wall between windows. The stiffness ratio of the bottom frame to the transition story is determined according to the seismic design code, guarantee the average strength coordination between the bottom story and the transfer story, and the lateral stiffness of the transition story is properly strengthened by setting structural tie columns and ring beams.

3. 3. Serious Destruction of Frame Columns on the Bottom Story When the vertical load excessively larger, the smaller longitudinal section and the concrete strength are insufficient; the longitudinal reinforcement will buckle into a lantern shape, the stirrups in the column will break or fall off, and the column loses its bearing capacity in the form of buckling failure, as shown in Figure 5.



(a) Partial collapse of a transition layer wall

(b) Serious damage to the wall between windows in the transition layer

Figure 4. Serious damage to the transition layer

Figure 5. Serious damage to the top of a bottom frame column

The top of the column and joint are under the combined action of the variable reinforcement, variable diameter, and shear and axial force; together with insufficient stirrups or poor anchorage results in serious failure to the joint location. The space effect of the story and the distributed reinforcement across the story, and the fact that the reinforcement of beams is frequently over-matched in the empirical design, bring about the empirical bending bearing capacity of the end section of frame beams being larger than that of the beam without considering the story action [3]. In the weak layer, the allocated shear force of the frame columns increases, and the shear strength is insufficient. Reciprocating seismic action causes the beam-column joints to be in the state of composite stress. The design should be carried out in strict accordance with the seismic code, and the construction quality shall be guaranteed to improve the structural integrity.

3. 4. Serious Destruction of Walls A portion of the bottom frames and upper masonry structures are basically intact. However, the rear longitudinal walls are seriously damaged in cases of both ensemble and partial collapse. This is observed because the mechanical properties of the frame comprising reinforced concrete beams and columns are different from those of the masonry walls. Additionally, buildings with a prefabricated slab roof structure have poor integrity. Under horizontal and vertical seismic action, the frame beams, columns, masonry walls and roofs hardly work well together. Local components of the structure may concentrate forces and enter into plastic state or sustain failure ahead of time. After the local structural components reach the plastic state, the distribution of seismic action among the members under vertical loads is no longer simply based on the principle that the proportion of lateral stiffness in the elastic stage is allocated according to the ratio of lateral stiffness. Therefore, the seismic action of each component in the process of building vibration may be a dynamic distribution process. Simultaneously, because the deformation of the frame and masonry wall is inconsistent, the transmission path of a vertical load may changes [12, 13]. To a certain extent, the masonry wall acts as bottom seismic wall and filling wall, as shown in Figures 6a and 6b. Some of the bottom frames of the buildings are basically intact, and the upper masonry structures are seriously damaged. As shown in Figures 7a and 7b, without reasonable consideration of the stiffness settings of the upper masonry structure, enhance the bottom stiffness unilaterally, and the phenomenon of "upper flexibility and lower rigidity" appears. In addition, through field investigation, it is found that the grade of damage to the rear longitudinal wall is remarkable discrepancy due to the multiple orientation of the structure system.

The scattered points of serious damage are concentrated in the zone of Kuiguang Road and Kuiguang East 5th Street. Commonly, construction of buildings along the street direction. It is speculated that the earthquake action has particularly directional influence on the structure system. For the hybrid bottom frame structure (the bottom adjacent street surface is frame structure and the back street surface is masonry structure), in addition to a few amount of joint damage caused by construction quality, the frame beam and column in the front face of the street are generally lighter; thus, the window wall in the outer longitudinal wall of the bottom back street is seriously cracked, resulting in a generous number of X-shaped joints in the longitudinal wall. Partly serious damage buildings, the window walls

(a) Serious damage to the bottom seismic wall

(b) Local collapse of the bottom seismic wall

Figure 6. Seismic Damage Characteristics of Walls

(a) Serious damage to a window wall

(b) Serious damage to the wall under the window

Figure 7. The bottom frame basically intact, and the upper masonry structure is seriously damaged

(a) The side of the mixed bottom frame structure near the street is basically intact

(b) Serious shear failure of the rear longitudinal wall on the side of the back street of the mixed bottom frame structure

Figure 8. Serious shear failure of the rear longitudinal wall on the side of the back street of the mixed bottom frame structure

even collapse, and large-scale failure, which leads to the collapse of the first story on the back street and results in the overall tilt of the building backwards, as shown in Figures 8a and 8b; therefore, insufficient width setting, and weak resistance. Most of these buildings have been seriously damaged and cannot meet the requirements of current seismic codes, and need to be strengthened or demolished [5]. The structure type of the bottom should be reasonably arranged to avoid local force inconsistency due to the mixed structure of the bottom; the stiffness ratio control of the bottom and the upper structure should be given full attention.

3. 4. A Plenitude Number of BFSWMS after 2000 Basically Intact Investigation of the BFSWMS of Du jiang weir urban areas, which in a multi-intensity zone was undertaken by the authors. After 2000, a plenitude number of aseismic designs were used for the roofs of the bottom story and for the transition story, normally adopting cast-in-situ or assembled monolithic concrete slabs, and the upper masonry structures use assembled reinforced concrete slabs with ring beams on the story.

According to the relevant chapters of the code for seismic design of buildings (GB50011-2001, China), buildings can reasonably meet the stiffness requirements for the bottom and transition storeys by establishing aseismic walls, which produce fine seismic resistance performance, as shown in Figure 9. A proportion of buildings with lower storeys have basically intact structures, which indicates that the seismic performance factors of the structure are related to the number and height of storeys.

Figure 9 Basically intact BFSWMS

3. 5. Aseismic Guidelines The structural system and damage characteristics of BFSWMS were analyzed, and its failure mechanism is maked a profound study. An effective aseismic guideline to resist seismic action is put forward as follows:

(1) The structural system shall be calculated in strict accordance with the seismic design code, and nsure reasonable layout of vertical and horizontal stiffness, clear load transfer route. The assumed force mechanism of seismic design is similar to the actual situation under the action of earthquake.

(2) Reasonable setting of anti-seismic wall or infilled wall at the bottom story. According to the seismic code for buildings (GBJ11-89, GB50011-2001, GB50011-2010), effectively limit the average strength and stiffness ratio between the transition story and the bottom story to avoid the formation of weak story at the bottom or the transition story.

(3) In seismic design, the seismic mechanism of "strong column and weak beam" is plenitude considered. Plastic hinges appear at the end of beams under strong earthquake, which can dissipate energy and reduce vibration to a certain extent, thus reducing the impact on other components.

(4) Adequate attention should be paid to the bottom aseismic walls or infilled walls, which absorbs a portion of energy and plays the role of the first line of defense under the reciprocating action of earthquake ground motion, and should be included in the seismic design calculation.

(5) In strict conformity with the seismic code, reinforced concrete cast-in-place floor or assembled monolithic floor with strong integrity are used in the bottom and upper story. Reasonable setting of tie columns and girders in the transition story can improve its ductility and average strength, avert damage of transition story caused by failure of short columns

(6) Guarantee the stirrup spacing of the bottom frame members, the spatial arrangement of longitudinal reinforcement, the reinforcement at the joints, the strength of mortar, and improve the quality of construction work.

4. CONCLUSIONS

In this paper, we have made a comprehensive investigation of the seismic damage of the BFSWMS in the Du jiang weir area and performed a statistical analysis of the data. It can be seen that the main causes of the direct damage in multiple grades derives from the influence of the different building ages, use of seismic design, construction quality, stiffness ratio of the bottom story to the transition story, stiffness angle and direction of seismic action.

During the investigation, a plentiful number of BFSWMS were found in the 1980s and 1990s; these structures did not install anti-seismic walls or infilled walls at the bottom, resulting in excessive displacement of the bottom and serious damage to the transition story. The joint is seriously damaged, and excessive deformation under torsion. A portion of the aseismic walls or infilled walls designed for seismic resistance suffered serious collapse. However, the main frame and upper masonry structure were basically intact. A plentiful number of BFSWMS that have been designed and constructed since 2000 can produce better seismic performance in violent earthquakes and achieve the design requirement that buildings experiencing "violent earthquakes do not collapse". In addition, it is found that the design of storey height also affects the seismic performance, which verifies the theoretical guidance of the relevant chapters of the code for seismic design of buildings (GB50011-2001, China). The symmetry and consistency of the building shape should be guaranteed, the concentration of stress should be avoided as much as possible, and the stress concentration areas should be strengthened. It is necessary to ensure that the bottom frame column has sufficient strength so that the stirrup spacing at the top of the column is narrow enough to guarantee the stiffness of the bottom story and that the stiffness ratio between the bottom story and the transfer story is reasonably controlled; this allows for the stiffness coordination of the different structural forms of the junction floors. Thus, avoiding complex structures and improving the overall seismic performance of the structure.

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چکیده

برای درک ویژگی های آسیب زمین لرزه ای ساختمان ها دیوارهای پایه ساختمان و بررسی عملکرد زمین لرزه ای آن، نتایج حاصل از آسیب های زمین لرزه ای سازه های دیوار فریم در دو جیانگ ویور توسط زلزله ون چوان در تاریخ ۱۲ مه ۱۳۸۶ در چین، مورد بررسی و مطالعه قرار گرفت . ارزیابی آسیب زمین لرزه ای به دیوار سنگ فرش دیوار در شهر Du jiang Weir نشان داد که آسیب به نوع سیستم ساختاری جدی بوده و شامل آسیب به چارچوب پایین، طبقه پایین، طبقه گذار، گره پایین و دیوار طولی عقب، ترکیب با ویژگی های شکست، دلایل شکست و مکانیزم، مورد تجزیه و تحلیل قرار گرفته و اندازه گیری های مربوط ارائه شده است. با این حال، تعداد قابل توجهی از ساختارهای سنگ تراشی دیوار زمین لرزه ای پایین BFSWMSs پس از سال ۲۰۰۰ اساسا آسیب دیده نیستند. تیم بازرسی میدانی از ۲۱۷۸ نمونه ساختمانی و از مشاهدات گروه شهری را نمونه برداری نموده اند. تعداد قابل توجهی از ساختمان ها به زمین لرزه تقویت شده، عملکرد زمین لرزه ای بسیار خوبی در زلزله ونچوان نشان داده اند، که نقش عوامل غنی سازی زمین لرزه ای کافی را در طراحی ساختاری نشان می دهد. با تحقیق و تجزیه و تحلیل آسیب زمین لرزه ای تجربی آن، اقدامات اصلی برای بهبود عملکرد زمین لرزه ای ساختاری مهیا گردید. نتایج تجزیه و تحلیل بالا می تواند مرجع برای طراحی زمین لرزه ای و بازنگری مقیاس شدت زمین لرزه ای را فراهم کند.

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