Shaking table test on seismic response properties of "Shicras," stones wrapped in vegetable fiber bags

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Paper:

Shaking Table Test on Seismic Response Properties of "Shicras," Stones Wrapped in Vegetable Fiber Bags

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[Received February 27, 2013; accepted April 17, 2013]

Unique foundations consisting of stones wrapped in vegetable fiber bags called *shicra* ("woven") have been found in many Pacific coast ruins constructed about 5,000 years ago as shrines in Peru. A shaking table test was conducted to investigate earthquake response properties of these shicra foundations. Results showed that in base isolation performance, shicra foundations "rolled" during earthquake vibration the same as in the case of roller base isolation systems.

Keywords: Peru ruins, shicra foundations, shaking table test, base isolation system

1. Introduction

A number of ruins that are considered to be among the oldest shrines on the American continent and dating up to 5,000 years ago have been found in coastal Peru. This is evidence that there was an ancient civilization in South America emulating the Four Great Civilizations, Egypt, Mesopotamia, Indus, and China, attracting archeological attention. The ruins discovered include the Caral Ruins (**Fig. 1**), which have been designated a UNESCO World Heritage Site, the Las Shicras Ruins, the Las Aldas Ruins, the Aspero Ruins, and the Vichama Ruins. Numerous shicras – stones wrapped in vegetable fiber bags (**Fig. 2(a)**) – were unearthed at many of these ruins.

At these ruins, masonry shrines made using adobe or stones were built on stylobates of stone and the like. Once constructed, shrines were buried and became bigger, higher stylobates as they were renewed, and new shrines were built on top of them – a method called shrine renewal. Repeating this renewal made a shrine pyramidal. Shicras were used as backfill in shrine renewal. These vegetable fiber bags binding stones together appear to have contributed to increasing the stability of the structure, whereas stones alone, with fewer inner friction angles, could not possibly have achieved sufficient stability as a structure. In short, shicras were used with the aim of increasing shrine stability against long-term loading. At the same time, vegetable fiber bags were considered advantageous in transportation and helpful in construction.

Moreover, considering the importance of the shrines as buildings, the authors are focusing on the behavior of shicras during earthquakes, namely the effect of schicras against earthquake vibration, since many of the shrines using shicras have remained standing for approximately 5,000 years in a seismically active area. It is understood from this long-term standing that the aim of using shicras was to ensure stability against long-term loading, as mentioned above, whereas the same technology might have had some, even unexpected, effect or significance for reduction of earthquake vibration. Research on this occurrence is useful in understanding the level of ancient experience-based technologies comparing with current technologies.

In this research, "shicra," or backfill used in shrine renewal, was faithfully reproduced by forming Peruvian juncaceous vegetables into a bag form in Peru and response properties to earthquakes with reproduced shicra used for shicra "foundations" were studied using shaking table tests. This paper reports the effect of shicra on earthquake response confirmed in shaking table tests.

2. Shaking Table Tests

In order to understand the dynamic behavior of shrine structures on shicra foundations during earthquakes, shaking table tests was performed using test bodies imitating shicra stylobates that were reproduced as faithfully as possible. Tests used a one-dimensional shaking table of the Building Research Institute. The shaking table

Fig. 1. Caral ruins.

(a)

(b)

Fig. 2. (a) Unearthed shicra, (b) reproduced shicra.

was 3.0 × 4.0 m and had a vertical supporting capacity of 20 tons, a maximum acceleration of ±1.0 G when a 20 ton weight was loaded, and a stroke of ± 150 mm.

2.1. Shicra Reproduction and Test Bodies

Shicras were reproduced for tests based on those unearthed in the Caral and Las Shicras Ruins. Stones with a diameter of 150 to 200 mm were put in bags made of *junco* belonging to the same juncaceous family as unearthed vegetables and formed into balls approximately the same size as the original ones with a diameter of approximately 30 cm. **Fig. 2(a)** shows a shicra unearthed in the Las Shicras Ruins compared to **Fig. 2(b)** of a shicra reproduced in this research. Note that the tensile strength of a bag vegetable fiber rope was 1200 N on the average.

Reproduced shicras were put in a steel frame, 1200 × 1200 mm and 100 mm tall fixed to the shaking table and heaped in the same manner as ruins to imitate a shicra foundation. A 1-ton steel plate – a 1000 × 900 mm plane 150 mm deep – was put on the foundation as a simple structure model representing just a mass of shrine building used for the purpose of understanding dynamic properties of the shicra foundation excluding the effect of dynamic properties of structures.

Expand metal was welded to the bottom of the steel frame and to the lower part of the steel plate, in order to prevent sliding with shicra foundation. No sliding happened was confirmed by the displacement measurements in the tests. A model made of heaps stones without shicra, namely, a stone-only foundation, was set next to the shicra model for comparison and both test bodies were shaken at the same time, as shown in **Fig. 3**.

2.2. Outline of Tests

The purpose of tests was to investigate earthquake response properties of shrine buildings in case constructed on shicra foundations and influence of number of shicra courses. Courses of shicras were 1, 2, and 3. Stones were heaped to the height corresponding to that of the shicra foundation in the case of the stone-only foundation. Note, however, that in the case of the stone-only foundation corresponding to 3 courses of shicras, which might collapse, the height was the same as that corresponding to 2 courses of shicras to ensure safety in experiments.

The shicra foundation was heaped in the same manner as shicras unearthed in the Caral Ruins. **Fig. 4** shows 2- and 3-course shicra foundations.

Input waves of shaking were based on seismic records from the 1940 Imperial Valley Earthquake at El Centro, CA (El Centro wave), from the 1995 southern Hyogo prefecture earthquake at the Kobe Meteorological Observatory (JMA Kobe wave), and from the 2004 Niigata Chuetsu Earthquake in Kawaguchi (Kawaguchi wave), along with sine waves and sweep waves with different frequency properties at the same acceleration amplitude.

The authors measured the acceleration and displacement of the shaking table, foundation top, and steel plates mounted on the foundations.

Cases of shaking are listed in **Table 1**.

3. Test Results

3.1. Horizontal Loading Tests

Before performing shaking tests using the shaking table, static horizontal loading tests were carried out in which steel plates mounted on shicra and stone-only foundations were joined with a lever block and pulled each other, then response properties during horizontal force acting on each foundation were investigated. **Fig. 5** shows an overview of static horizontal loading tests.

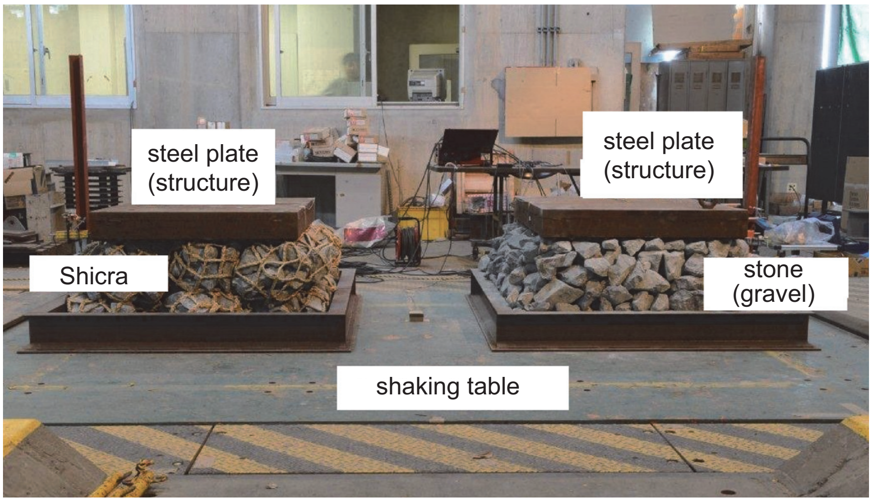


Fig. 3. Test set up.

(a)

(b)

Fig. 4. (a) Two-course shicra foundation, (b) three-course shicra foundation.

Table 1. Cases of experiments.

Experiment cases		
No.	Case	Test body
1	Static tensile test	Initial height of test body: 30 cm (1 course) for shicra foundation and 28 cm for stone only foundation
2	Kawaguchi wave 100%	
3	El Centro wave 100%	
4	JMA Kobe wave 100%	
5	Sweep 1 Hz-20 Hz, 30 gal	
6	Static tensile test	Initial height of test body: 61 cm (2 courses) for shicra foundation and 61 cm for stone-only foundation
7	Kawaguchi wave 100%	
8	El Centro wave 100%	
9	JMA Kobe wave 100%	
10	Sweep 1 Hz-20 Hz, 30 gal	
11	3 Hz sine wave shaking	
12	4 Hz sine wave shaking	
13	5 Hz sine wave shaking	
14	Static tensile test	Initial height of test body: 88 cm (3 courses) for shicra foundation and 61 cm for stone-only foundation (same as 2-course shicra foundation)
15	Kawaguchi wave 100%	
16	El Centro wave 100%	
17	JMA Kobe wave 100%	
18	Sweep 1 Hz-20 Hz, 30 gal	
19	3 Hz sine wave shaking	
20	4 Hz sine wave shaking	
21	5 Hz sine wave shaking	
22	3 Hz sine wave shaking, maximum 800 gal	

Figure 6(a) shows the horizontal displacement of top steel plates in relation to horizontal loads in the case of the 1-, 2-, and 3-course shicra foundation. **Fig. 6(b)** shows the horizontal displacement of steel plates in relation to horizontal loads in the case of the stone-only foundation with corresponding height. (Note that the stone-only foundation corresponding to the 3-course shicra foundation is not shown because it has the same height as the 2-course shicra foundation.)

Comparison results showed that shearing stiffness of 2- and 3-course shicra foundations decreased with increasing loading compared to stone-only foundations. Stones are less likely to rub against each other in shicra foundations than in stone-only foundations. There seems to be no clear relationship between shearing stiffness and the height of heaped shicra foundations, which may be affected by the difference in the rubbing of stones together due to the positional relationship between shicras.

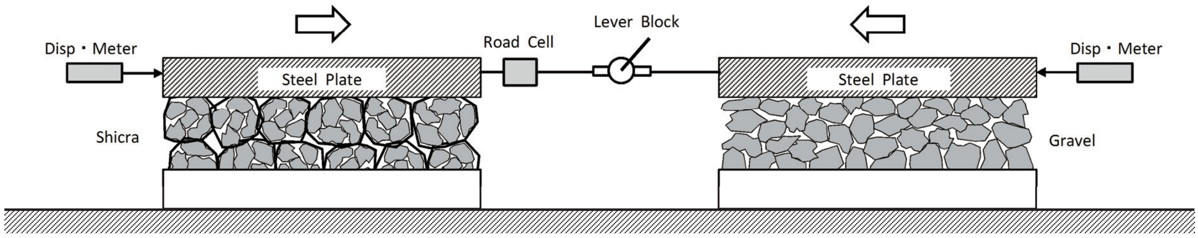


Fig. 5. Overview of static horizontal loading tests.

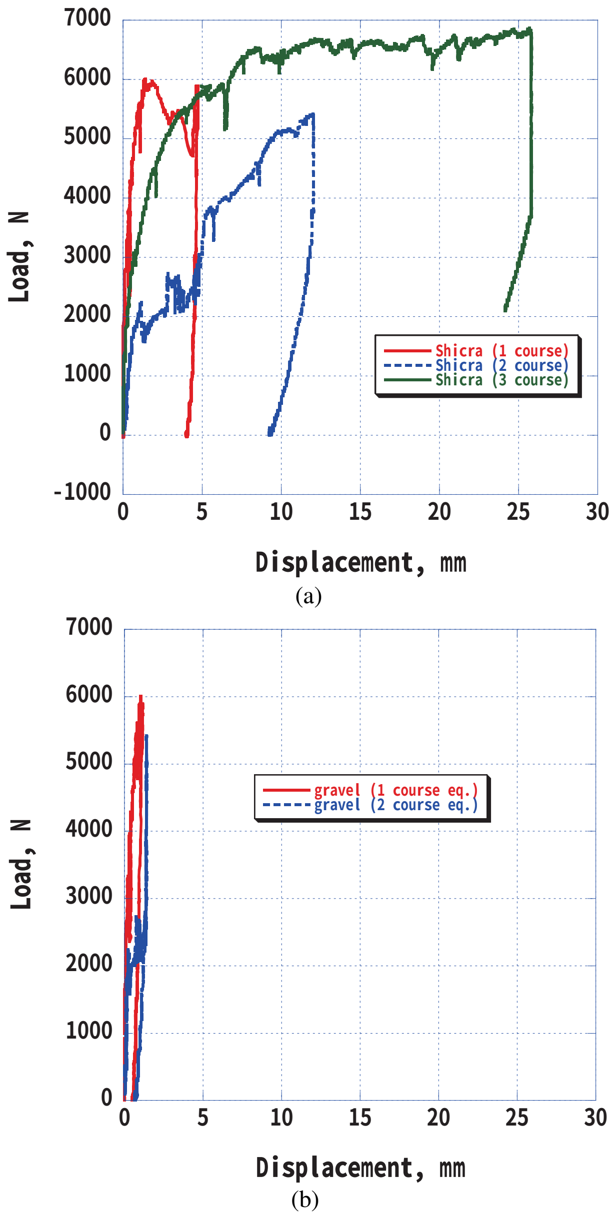


Fig. 6. (a) Horizontal loading of steel plate on shicra foundations in relation to displacement, (b) horizontal loading of steel plate on stone-only foundations in relation to displacement.

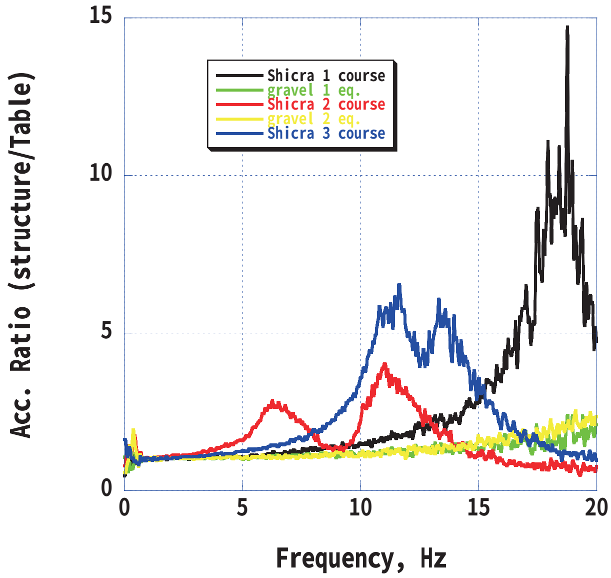


Fig. 7. Relationship between acceleration response magnification and frequency.

3.2. Shaking Tests

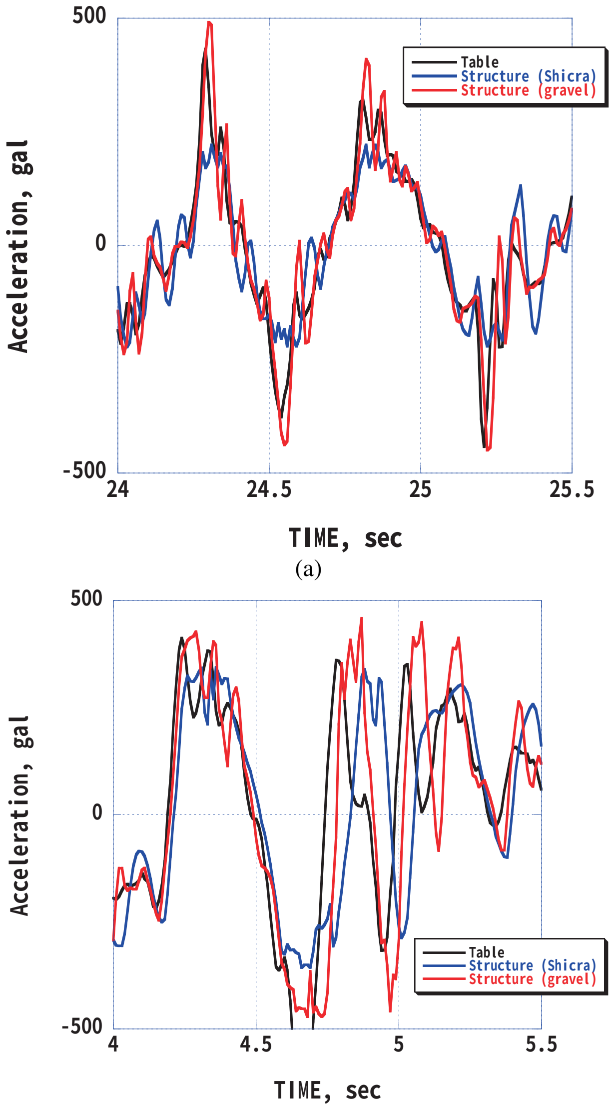
(1) Frequency response properties

In order to understand seismic response properties of shrine structures built on foundations, sweep shaking was performed. The ratio of steel plates acceleration to shaking table acceleration (acceleration response magnification) and frequency were measured in shaking table acceleration of 30 gal at a frequency of 0.1-20.0 Hz. The relationship between acceleration response magnification and frequency is shown in **Fig. 7**. Unique amplification properties were observed in the case of shicra foundation, whereas almost no amplification properties were observed in the case of stone-only foundation.

(2) Seismic response properties

Time-history acceleration waveforms were measured for steel plates on shicra and stone-only foundations in relation to input seismic acceleration waveforms by inputting the Kawaguchi wave to 1- and 2-course shicras. **Fig. 8** shows enlarged diagrams of the largest input acceleration. **Fig. 9** shows examples of time-history acceleration waveforms of steel plates in the case of 2-course shicra when shaking was conducted by gradually increasing input acceleration under sine waves with frequencies of 3 and 4 Hz.

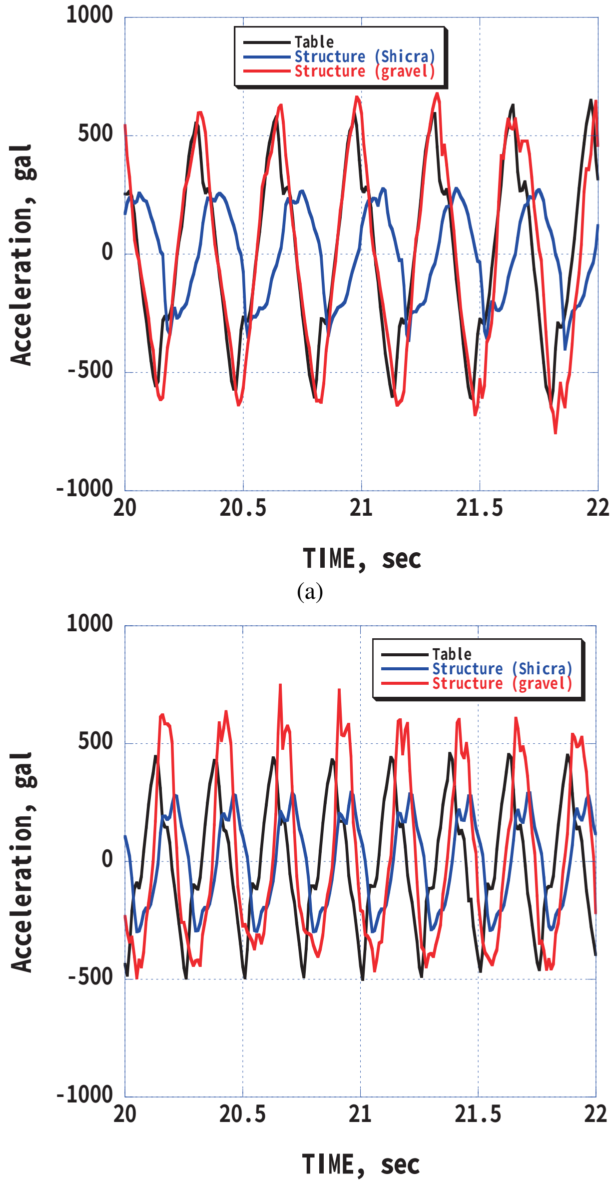
When shaking table acceleration in the above results exceeds approximately 300 gal, steel plates used as mass models of shrine clearly show a tendency to produce acceleration that does not exceed than that in the case of shicra foundations, but shaking table acceleration is almost the same, with no particular response amplification, as that of steel plates below 300 gal. In the case of stone-



(a)

(b)

Fig. 8. (a) Acceleration waveforms (1-course shicras, Kawaguchi wave input), (b) acceleration waveforms (2-course shicras, Kawaguchi wave input).



(a)

(b)

Fig. 9. (a) Acceleration waveforms (sine wave of 3 Hz input), (b) acceleration waveforms (sine wave of 4 Hz input).

only foundations, however, shaking table acceleration is almost the same as that of steel plates throughout the domain, indicating behavior as a rigid body with no response amplification.

Figure 10 shows the relative displacement of steel plates on 2- and 3-course shicra foundations in response to the shaking table in comparison to input acceleration. Relative displacement of steel plates to the shaking table is minimal until input acceleration exceeds 300 gal, although major displacement is generated over 300 gal. These response properties are observed in shicra foundation behavior in shaking tests. Experiment results demonstrate that individual shicras rotate when vibration occurs to some extent occurs in the case of the shicra foundation, showing behavior similar to rolling seismic isolation as shown in **Fig. 11**. Steel plates also showed lateral movement due to rolling and upward movement, which is considered to be affected by the imperfect circular shape of shicra foundations.

Rolling behavior of stones was not observed for stone-only foundations, whereas although outer parts of these foundations were scattered into pieces when higher acceleration was generated, which demonstrates that shicra foundations are more stable against collapse than stone-only foundations. It is thus easily understood that shicras were used from the perspective of its stability effects on shrine foundations and from the ease of transportation. There is no way of telling, however, if ancient people recognized the seismic isolation effect confirmed in this experiment. Note that since the Nasca plate has subducted off the coast of Peru and periodic huge earthquakes probably occurred there, ruins remaining are likely to have withstood such huge earthquakes thanks to response reduction resulting from the effect of rolling seismic isolation.

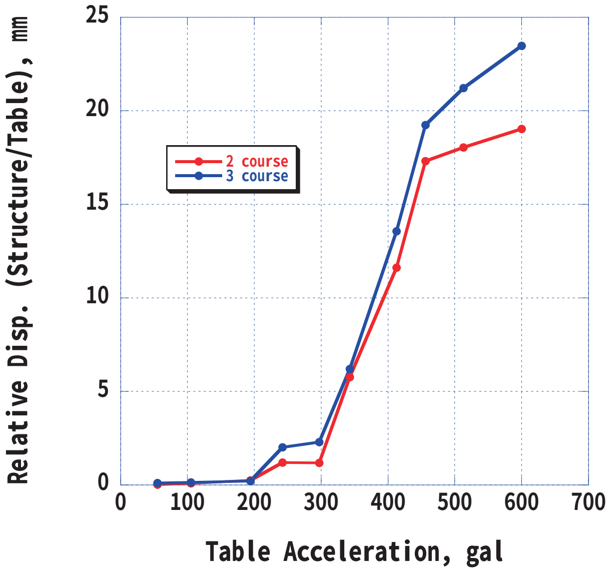


Fig. 10. Relative displacement of shaking table to structure models on shicra foundations.

Fig. 11. Shicra foundation rotation.

4. Conclusions

In order to study the response of shrines built on shicra foundations, shaking table experiments were conducted using test bodies imitating stylobates of shrines. Experiment results suggest the following findings:

(1) Shicra foundations displayed behavior similar to rolling seismic isolation. Steel plates represent a mass of shrine buildings on shicra foundations did not produce acceleration exceeding that even when shaking table acceleration exceeded approximately 300 gal. This indicates that the friction coefficient in rotating motion is 0.3. In this case, shrine structures withstood huge earthquakes if they have strength sufficient to remain standing under vibration of 300 gal. Note that the value 300 gal is not absolute because shicras used in experiments may differ in detail from the original shicras, even though they were reproduced as faithfully as possible. At the least, the seismic isolation function of the shicra is certainly proven.

(2) Stone-only foundations showed almost no response when shaken and moved in the same manner as the shaking table. More acceleration would be generated in shrine structures with stone-only foundations than in the case of shicra foundations during huge earthquakes. Outer stones collapsed when shaken.

(3) The friction coefficient of shicras remains almost unchanged, even after repeated shaking, which indicates that shicras possess the same stable properties as sliding (rolling) material.

Acknowledgements

This paper has been submitted with the aid of the Study on Improvement of Disaster Reduction Technology against Earthquakes and Tsunami in Peru (chief researcher: Prof. Fumio Yamazaki, Chiba University) assisted by the Science and Technology Research Partnership for Sustainable Development, JST-JICA. The authors wish to express their sincere thanks for their invaluable assistance.

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