

## DEFORMATION MECHANISMS OF RETAINING MASONRY WALLS SUBJECTED TO EARTHQUAKE

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### ABSTRACT

Masonry walls of railways are often used to protect cut slopes and retaining walls on the toe of embankment slopes in Japan, because their materials are easily available. In urban areas in Japan, therefore, there are a number of masonry walls of this type (still in use) that were built when the railway was constructed. We investigated the masonry walls of this type along railway lines, studied their standard structure, and performed shaking table tests on the models of such masonry walls. As a result, we were able to clarify their deformation mechanism and the effect of the building process (dry or wet masonry), height of wall and horizontal resistance of the foundation on their behavior during earthquakes.

Keywords: masonry wall, railway lines, shaking table test, deformation mechanism

### INTRODUCTION

In Japan, there are many masonry walls located as shown in Figure 1 along railway lines. Although, seismic reinforcement for various structures is progressive after the Hyogo-Ken- Nanbu earthquake occurred, reinforcement of masonry walls has not yet started. Reason of it is that a destabilization mechanism of masonry is unclear, because there have not been any studies on masonry stability during earthquake (e.g. O'Reilly, Bush, Brady and Powrie, 1999). Therefore, we must clarify the destabilization mechanism, and develop a method for seismic safety evaluation based on the mechanism and a proper quakeproof method. Accordingly, this paper presents (1) actual conditions of structures of the masonry walls, which exist on the railway line of the railroad, (2) a result of shaking table tests with model masonry walls, which made the actual condition, (3) the destabilization mechanism of the masonry wall during earthquake.

### INVESTIGATION

#### Characteristics of masonry walls located along railway lines

Ashlars of a form as shown in Figure 1 apply to most of the masonry walls constructed along railway lines. Figure 2 shows a typical cross section. A masonry work of ashlar is roughly divided into two types: "dry masonry" and "wet masonry". Dry masonry is a method of filling up a stone without using

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back filling concrete and wet masonry is the method by which ashlar unified with low strength mortars. In addition, there are just some walls that only the contact side of the stones was glued with mortars. Figure 3 shows a masonry wall of 16.9 km in length classified by respective heights located in Tokyo metropolitan area. That figure shows the dry masonry and the wet masonry respectively. Where the height of the wall is lower than 4-m, almost the same length of dry masonry and wet masonry are located. Where a height of a wall is higher than 4m, the length of dry masonry wall decreased, and the length of wet masonry wall conversely increased. Although the dry masonry of the lower height than 8-m does not exist, the wet masonry of the higher than 10m exists to the extent of approximately 900-m. An average of the height of the dry masonry walls is 3.5-m (a standard deviation is 1.8-m), an average of the height of the wet walls is 6.0-m (a standard deviation is 2.4-m), an average of the whole height including the dry and the wet masonry walls is 5.5-m (a standard deviation is 2.2-m). Figure 4 shows a distribution of angles of the masonry walls in Tokyo metropolitan area. 80% of the walls have the angle of 73.3°. Though the dry masonry steeper than 73.3° does not exist, many wet masonry walls of 78.7° exist. Therefore, a standard slope of the dry masonry wall is 73.3°, and it is conceivable that wet masonry walls applied when the execution of the steeper slope is necessary.



Figure 1. A view of masonry walls on railway lines

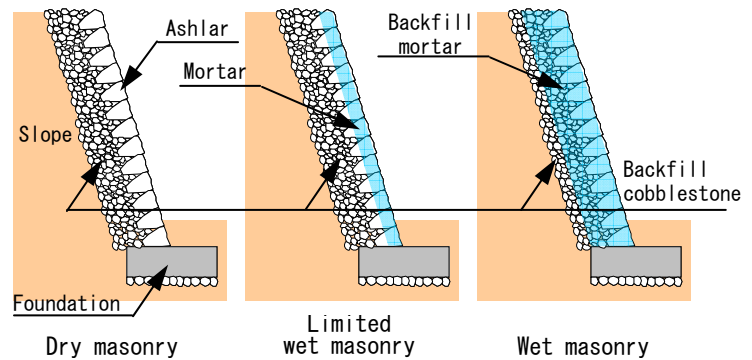


Figure 2. Typical cross sections

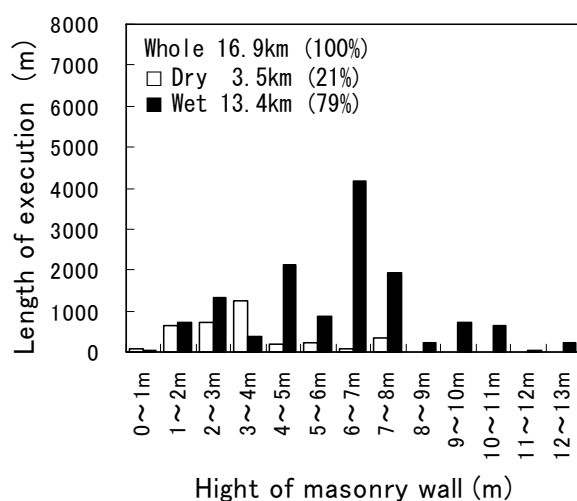


Figure 3. Distribution of height of the masonry wall in Tokyo bloc

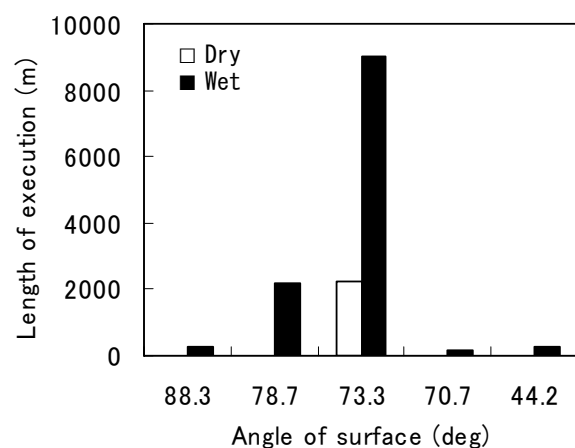


Figure 4. Distribution of angle of the masonry walls in Tokyo bloc

## EXPERIMENTAL CONDITION

### Property of models

We made models of masonry walls based on the structure of the actual wall, which was above mentioned, and applied these models to the shaking table test. We made models adapt to a similarity rule for model vibration tests of earth-structures (Kagawa, 1978). Figure 5 shows a 1/3 scale test model of the prototype wall of the height of 3-m. A model of the ashlar applied to the experiment is made in dimensions as shown in Figure 6. A slope of the wall is  $73.3^\circ$ . Pebbles, which have a grain size distribution as shown in Figure 7 applied to backfill cobblestone of the models. A density of backfill cobblestone layer is  $1.6 \text{ g/cm}^3$ . This is a value of result from the compaction tests that as examined in advance and it is consistent with a value of real walls. It is one of main purposes of the experiment that we obtain behaviors of the wall itself during earthquake; therefore, we made a stable model as a slope behind the wall. Strength of mortar for wet masonry wall is  $1.3 \text{ MN/m}^2$ . Two kinds of structure of Figure 8 applied to the foundation of the model. One is a foundation fixed on the table, and another one permits displacement of itself in the horizontal direction. In case of test that permitted displacement, we applied pedestals, which had two kinds of frictional coefficients of 0.159 and 0.350. Table 1 shows the test conditions.

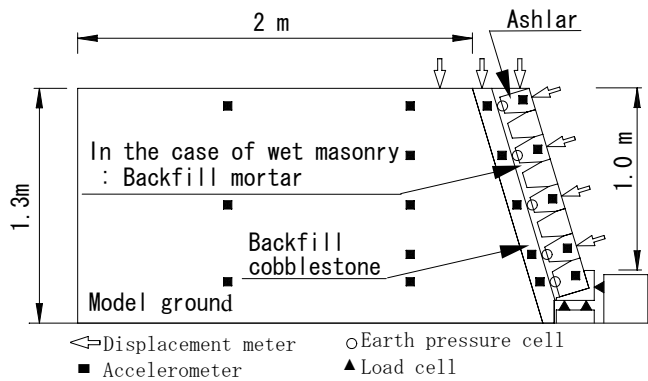


Figure 5. Cross section of the model

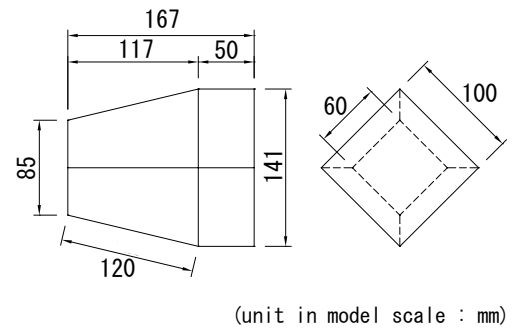


Figure 6. Dimensions of model ashlar

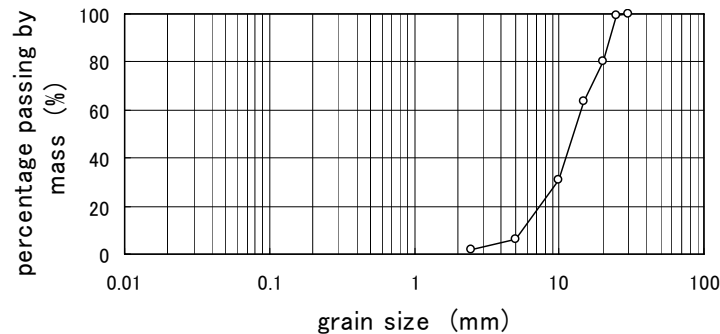


Figure 7. Particle size distribution of backfill cobblestones

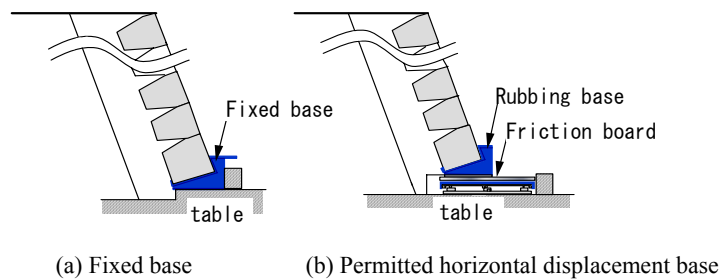


Figure 8. Cross section of the foundation model

Table 1. Test cases

Test No	Piling method	Height	Condition of base
1	dry	1.0m	fixed
2	wet	1.0m	fixed
3	dry	1.5m	fixed
4	wet	1.5m	fixed
5	dry	0.6m	fixed
6	dry	1.0m	frictional coefficient $\mu=0.16$
7	dry	1.0m	frictional coefficient $\mu=0.35$

### Measurement item

Figure 5 shows the arrangement of the test apparatus. We measured response acceleration of ashlar, backfill cobble stone layer and slope, and roof settlement, horizontal displacement of ashlar, earth pressure that sustained ashlar, horizontal and vertical load that sustained the foundation of wall. However, in case of No.6 and No.7, we did not measure the vertical load of foundation.

### Input acceleration

An input acceleration was a sinusoidal wave. A frequency applied to the test is that 2Hz shown as a design response spectrum (e.g. Railway Technical Institute, 1999) was converted into the equivalent in the scale of the model. We converted frequency into the 1/3 scale model based on the similarity rule, and applied 5Hz to the sinusoidal wave. We increased the acceleration input to one model in the experiment of one case gradually. We input the acceleration of specific amplitude twenty times, thereafter, measured a distribution of the deformation of the wall, furthermore, input the acceleration, which increased 50-gal, and operated again. We increased input acceleration until the model wall collapsed or the acceleration reached 980-gal (maximum capacity of the test apparatus).

## BEHAVIOR OF MODELS

### Response acceleration, top settlement, load of base, displacement, earth pressure

Figure 9 and 10 show a respectively indicate measurement where the input acceleration is 600-gal. A response acceleration of the top ashlar is decrease a little to input acceleration as shown in Figure 9, its dynamic magnification factor is 0.88. Therefore, it shows that a behavior of the top ashlar is a little different from the whole of wall and the base. Figure 9(3) shows that a settlement of the top of backfill cobble stone layer is increases with cyclic loading times increasing. A disposition of the settlement to increase at the early period of operation is gentle, after that, the settlement is almost on the increase in the same slope from the starting two seconds to five seconds. It subsided 20mm with cyclic load of 20 times. A comparison of Figure 9(4) and Figure 9(5) shows a difference in the vertical stress of the base that measured in the front of foundation and the back. While a compressive load of the front somewhat increases, the load of the back decreases rapidly after 0.5 seconds. From these measured values, the behavior of the load indicates that the wall overturned gradually. Figure 10 shows the horizontal displacement amplitudes of four ashlar as shown in the Figure. The amount of increase of displacement amplitude and residual displacement of the ashlar piled to the top is large. As for the behavior of the top ashlar whose amplitude is the largest, the amplitude, which was approximately 1-mm with the first load, is on the increase even in approximately 3-mm with the twentieth load. Figure 9(6) shows the earth pressure acting on back of model ashlar. Though a change with the amplitude of the input acceleration is visible, the tendency of the increase or the decrease invisible.

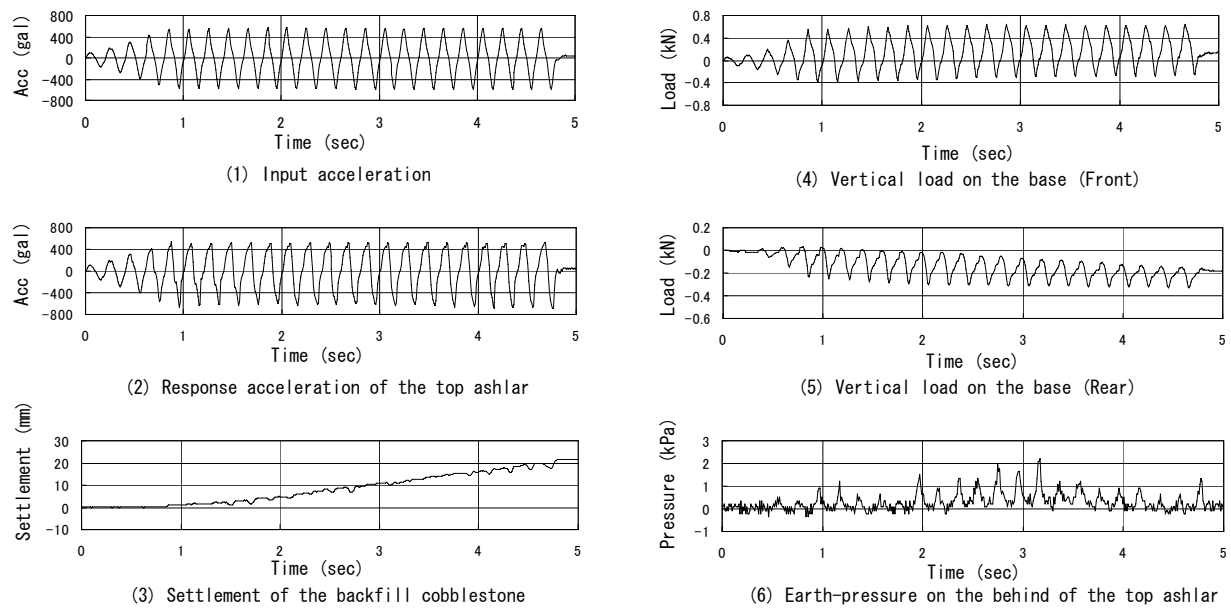


Figure 9. Measurement value of Test No.1  
(Input acceleration is 600gal)

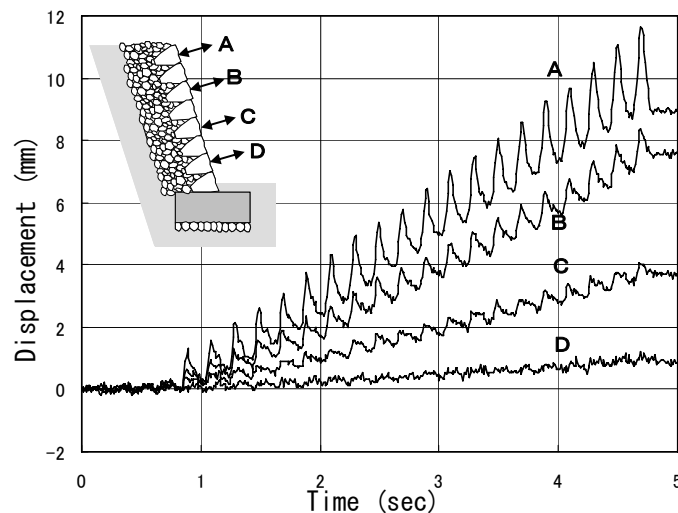


Figure 10. Displacement of ashlars of Test No.1  
(Input acceleration is 600gal)

### Influence of structural conditions

A decrease in response acceleration of ashlars indicates that the table has shaken separately with the ashlars; therefore, it shows that the wall begins to be destabilized. Accordingly, we discussed the influence, which a difference in the structure condition of each model of walls exerted on the change in the response acceleration.

### Effect of Height

Based on the experimental results of No. 1 to No. 5, we examined an effect of height of masonry wall affecting resistance to earthquake. Figure 11 shows the relationships between response acceleration and input accelerations of top cobblestones. In the case of dry masonry, both heights of the wall of 1.0-m and 1.5-m, the input acceleration that a remarkable decline begins to appear in the response acceleration is 600gal, and there is no great difference by the height. On the contrary, when compared

the decline tendency after response acceleration begins to decrease remarkably, a decline in the response acceleration of the higher wall is steeper than the lower wall.

### Dry and Wet masonry

Figure 11 shows the effect, which a difference in dry and wet masonry exerts on the relationships between the response and the input acceleration of the ashlar of the top. Though in case of dry masonry, the response acceleration of the wall of height 1.5m and 1.0m begins to decrease remarkably at the input acceleration 600gal, the response acceleration of wet masonry does not decrease in the input acceleration of less than 980-gal. As mentioned above, the behaviors of dry and wet masonry are greatly different, though the strength of the back fill concrete, which applied to wet masonry, is poor, as for the resistance to earthquake of wet masonry; it is conceivable that it is higher than dry masonry.

### Horizontal resistance of foundation

Relationships with input and response acceleration of the top ashlar of the wall of No.1 (fixed on the shaking table), No.6 (the coefficient of friction  $\mu=0.16$ ) and No.7 ( $\mu=0.35$ ) are shown in Figure 12. In case of which horizontal resistance to function in the foundation is big, the input acceleration that the response acceleration of the top ashlar begins to decrease is big. Especially, in case of a frictional coefficient 0.16, the response acceleration of the top stone begins to decrease input acceleration of 200gal.

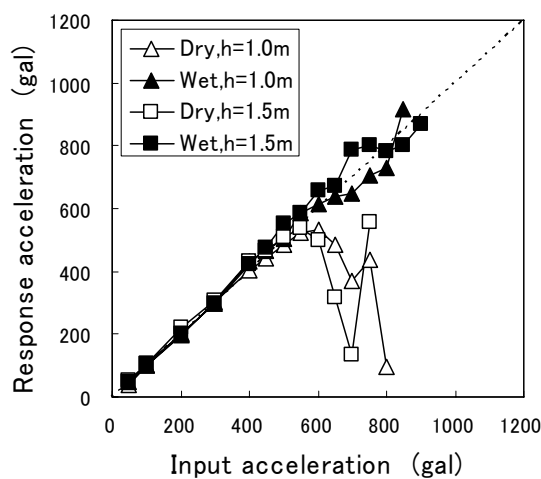


Figure 11. Influence which height and masonry work exert on response acceleration

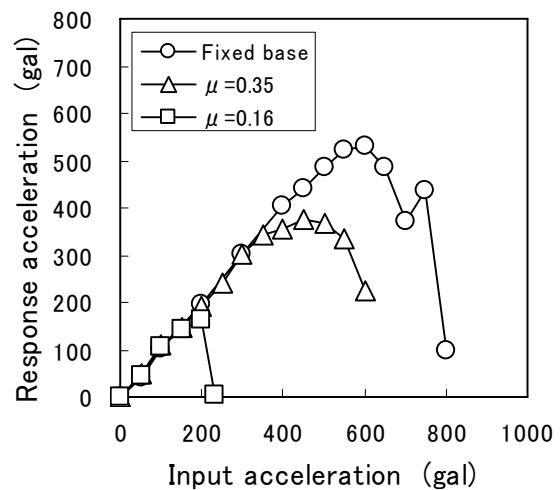


Figure 12. Influence which horizontal resistance exert on response acceleration

## DEFORMATION MECHANISM

The deformation path of the masonry wall caused by the increase in the input acceleration, which became clear in the shaking table test, is shown in the Figure 13.

### In a case of stiff foundation

In such a case that the foundation is stiff, it pursues the following process. 1) The inertia force of an earthquake to the front- direction of the wall acts on the ashlar, and a balance of ashlar shifts, and gravity position of the wall moves in front. The bigger inertia force, when acting on the wall, the amplitude of horizontal displacement becomes bigger and the relative displacement begins to occur between the slope and ashlar. 2) When the base of the wall is strong, the resistance force to act on the basics of the wall is big, therefore the higher part in the wall it is, the bigger amplitude of displacement occurs. With such a behavior, ashlar move to the front-side of the wall while it settling. 3) The inertia

force to the front direction of the wall ends and the inertia force to the back direction begins to act on the wall next. At this time, backfill cobbles exist at the back of ashlar, therefore the displacement occurs without ashlar being able to return to the origin position. 4) Such a process repeated, settlement and movement of backfill cobblestone accumulates the displacement of the wall gradually, and the wall results in the final collapse. When the wall collapses through the above-mentioned process, it shows the transformation form of the tumble mode. Such a process is shown in "In a case of stiff foundation" Figure 13.

#### In a case of not stiff foundation

1) In the case that the foundation is soft or the case as the horizontal resistance of the base of wall cannot look forward to it for a side gutter to be made at the base front, large amplitude of displacement appears at the ashlar in the lower part of the wall. 2) Therefore, before the backfill cobblestone begins to settle by doing a displacement by ashlar in the upper part of the wall, ashlar of the lower part are pressed in front of the inertia force. 3) Such behaviors repeated and the wall eventually collapses. When collapsing through such a process, the form of the transformation of the sliding mode appears in the wall. In this case, the displacement begins to appear in the wall in the comparatively small inertia force. Figure 13 shows the above mentioned deformation mechanism as to a case of poor foundation.

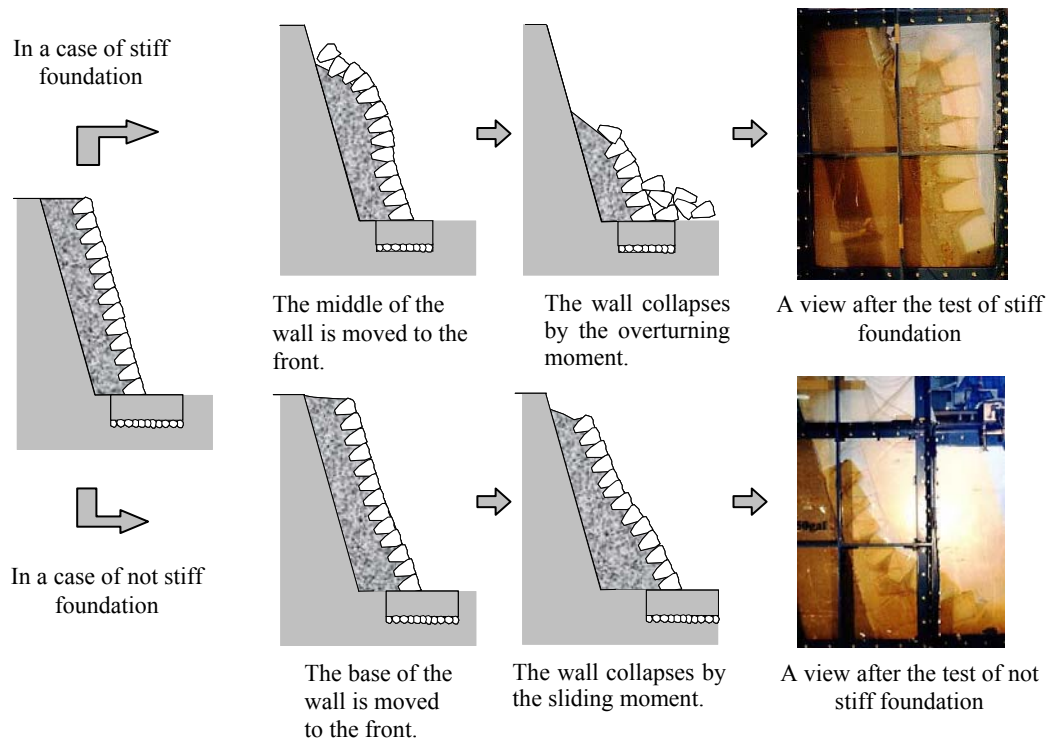


Figure 13. Deformation process of the masonry wall was due to the experiment

## CONCLUSIONS

We conducted simulation shaking table tests aiming at building a technique to evaluate reliability during earthquake about the masonry walls that exists along a railway line, it experimented on the model shaking table test.

The results of the model tests indicate:

- (1) Although the strength of backfilling concrete is less, the stability of wet masonry is higher than that of dry masonry.
- (2) The higher the wall, the lower the reliability is, and the influence which the horizontal resistance to act on the base exerts on the reliability is large.
- (3) The deformation accumulates in earthquake sinking cobblestone and moving and the wall collapses finally.
- (4) Where foundation is under solid condition, the wall shows the deformation form of a tumble mode, however, where foundation is under a poor condition, the wall shows the deformation form of a sliding mode.

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