This paper deals with how tsunami force acted on bridge girders when the Great East Japan Earthquake broke out on March 11, 2011. First of all, almost all data of bridge girders in the inundation area were collected. Satellite images in internet websites were introduced to make a quick survey on how many bridges were in the inundation area and how many of them were damaged. Detailed data on the bridges, such as dimensions and types, were obtained from authorities that have maintained those bridges. For damage analysis of bridge girders, Prof. Kosa’s method was introduced to see whether bridges were washed away or not by tsunami. Motion pictures of the tsunami taken by residents when it happened were examined to evaluate the velocity and height of the tsunami. In order to examine how bridge girders were washed away, an experimental investigation was conducted using a big water channel. Hydrodynamic analysis was conducted to evaluate the test results. In addition, a new numerical simulation technique was developed to follow the movement of a bridge girder during the tsunami.

Key Words: tsunami force, bridge girder, satellite image, damage analysis, experiment

1. INTRODUCTION

The great East Japan Earthquake on March 11, 2011 caused the greatest tsunami that we have ever had in one thousand years in Japan. Compared to the damage caused by the earthquake itself, the damage due to the tsunami had much more serious impact to modern society in the eastern Japan area. It was a shocking scene showing a lot of bridges near the shore that were washed away while very few bridges inland suffered from the earthquake.

Since the Great Hanshin Earthquake in 1995, bridge engineers and researchers have been working hard on how to improve the seismic design of bridge structures. The damage to bridges caused by tsunami was completely out of our concerns because we had never had such damage since modern bridge technology has been introduced in one hundred years.

In the near future another big earthquake and tsunami are expected to break out in the western area of Japan. It is, therefore, an urgent issue to establish some guidelines concerning tsunami forces acting on bridge structures to strengthen bridge structures. The objective of this paper is to provide information to help establish the guidelines.

As the first step, it is necessary to discuss how to conduct the survey of whole bridges in the inundation area. Based on the collected data, a rather simple damage analysis was conducted. Although tsunami characteristics, such as velocity and wave height, are
essentially required, the data are not adequately obtained. Thus, it is necessary to discuss how to get the characteristics of tsunami by motion pictures taken by residents.

There were some cases of damage to bridge girders that are not easy to understand. For a specific case an experimental study was conducted. Water pressure on the bridge girder was measured. The test results are discussed with a hydrodynamic analysis.

A newly developed model is discussed to simulate how a bridge girder is washed away.

2. SURVEY OF DAMAGE IN BRIDGES

(1) Survey with satellite photo images

The number and the location of bridges in the inundation area were surveyed by satellite images shown on the internet. Figure 1 shows an example of these satellite images. By comparing satellite images taken before and after the earthquake, the locations and damages of bridges were recognized in most cases. The entire inundation area was visually inspected in the satellite photo survey.

However, since the tsunami carries large amounts of rubble and huge amounts of mud, some bridges could not be seen well when they were covered with them as shown in Fig.2. In such cases field surveys were conducted.

(2) Field survey

Every bridge that was found to be damaged in the satellite image survey was examined on site. In addition, undamaged bridges were also examined for the comparison discussed later. The total number of inspected bridges on site was more than 500.

The measured values on site are the length and the cross-sectional dimensions of girder, and the vertical distance from the water surface to the lower surface of girder (Fig.3) were measured on site. In the case of bridges whose girders were washed away, the original design documents were used as reference. In addition, the depth of water was measured using a wireless sonar device. These values were necessary for damage analysis.

(a) Before Earthquake (25th June, 2010)

(b) After Earthquake (6th April, 2011)

Fig.1 Satellite Images (Sizugawa).

Fig.2 Small RC bridge covered with mud and bush.

Fig.3 Measurement of dimension of bridge.
(3) Summary of survey

Figure 4 shows the locations of the damaged bridges. The distance from the northernmost bridge to the southernmost bridge is 530 km. The damaged bridges were concentrated on the San-riku Ria coast and the coast near the Fukushima Daiichi nuclear power plant. On the other hand, a small number of bridges were damaged in plain fields such as Sendai and Ishinomaki.

Figure 5 shows the run-up and inundation heights surveyed by the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group5). The run-up height in San-riku area was much higher than those in other areas. This was due to the higher wave heights in the Ria coast. Fukushima was another area where the run-up and inundation heights were high.

On the other hand, the inundation height in the Sendai Plain was lower than those in other areas. It can be concluded that a correlation exists between the wave heights and the number of damaged bridges.

The statistical data are summarized in Table 1. The total number of bridges within the inundation area was 1793 and the number of washed away bridges was 252.

In the Table 1 “damaged bridge” is defined as the bridge whose girders are moved or washed away. The damage to the guardrail and poles are not considered for the classification. The number of damaged railway bridges is 28, while 40 major road bridges are damaged. The damage rate of road bridges is relatively small (approximately 15%). On the other hand, the damage rate of railway bridges is high (37%).

It is because railway bridges are light in weight. The width of railway bridges are smaller than those of road bridges. Several railway bridges do not have slabs; hence, they are light in weight compared to road bridges. There are a considerable number of washed out bridge piers, which were not strengthened against earthquakes. In other words, seismic strengthening was not required for the piers because the weight of the steel bridge girder was relatively light to cause damage to the piers.

The number of municipal bridges in the inundation areas is much higher than that of railway, highway, and national route bridges. The number of damaged municipal bridges (Pref. road and others) is much higher than those of national route bridges.

3. DAMAGE ANALYSIS

As mentioned previously, the dimensions of bridges were measured as much as possible at the on-site survey. Consequently, the dimensions of 170 damaged bridges and 130 intact bridges were obtained. Other data, such as inundation heights and the elevation of bridges, were collected from the internet. By using these data, the safety ratio of each bridge was evaluated using the equation proposed by Shimizu et al.6). He assumed that the tsunami's force is mainly composed of drag, while the bridge girder resisted using frictional force.

![Fig.6 Simple model of safety of bridge girder.](image)

| Type of bridge     | Damaged | Unclear | No damage | Total |
|-------------------|---------|---------|-----------|-------|
| Railway           | 28      | 0       | 48        | 76    |
| Highway           | 0       | 0       | 3         | 3     |
| National route    | 15      | 0       | 77        | 92    |
| Pref. road        | 25      | 1       | 163       | 189   |
| Others            | 184     | 7       | 1242      | 1433  |
| Total             | 252     | 8       | 1533      | 1793  |
According to their research work, the drag of a tsunami acting on a bridge girder can be treated as a hydrodynamic force indicated by equation (1). This equation is Morrison’s formula, which is generally used to calculate flood and wind loads for the design of Japanese road bridges\(^7\).

\[
F = \frac{1}{2} \rho_w C_d v^2 A_h
\]

(1)

where \(F\) is the drag, \(\rho_w\) is density of water (1030 kg/m\(^3\)), \(C_d\) is the drag coefficient, \(v\) is velocity of water, and \(A_h\) is the projected pressure area of the girder in the horizontal direction. The drag coefficient for the wind load \(^7\) is applied in this study as shown in equation (2).

\[
C_d = \begin{cases} 
2.1 - 0.1 \cdot (B/D) & (1 < B/D < 8) \\
1.3 & (8 \leq B/D) 
\end{cases}
\]

(2)

where \(B\) and \(D\) are the width and height of the bridge girder, respectively. The resistance of the girder in the horizontal direction is mainly due to self-weight, and is computed using equations (3) and (4). The difference between these equations lies in the existence of buoyancy.

\[
S = \mu W
\]

(3)

\[
S = \mu (W - U)
\]

(4)

where \(\mu\) is the frictional coefficient (0.6, based on the research by Rabbat and Russel\(^8\)), \(W\) is the self-weight of girder, and \(U\) is buoyancy as computed by equation (5).

\[
U = \rho_w g V
\]

(5)

where \(V\) is the volume of the bridge girder under water.

The ratio of girder resistance \(S\) to tsunami force \(F\) is an index to judge whether a bridge girder is washed away or not by a tsunami. The indicator \(\beta\) that relates to the safety factor is introduced as shown in equation (6).

\[
\beta = \frac{S}{F}
\]

(6)

When \(\beta\) is smaller than 1.0, a bridge girder has a significant possibility of being washed away by a tsunami of a given magnitude. Although the velocity of the tsunami is most important in these equations, the observed records of the velocity of the tsunami are scarce at the site of bridge. Here, a constant velocity of 6.0 m/s is used for analysis. This value is the average velocity taken from recorded videos throughout the Tohoku area by Fu et al.\(^9\).

Figure 7 shows a number of bridges with respect to \(\beta\). Buoyancy is not considered in this figure. Some bridges were washed away even if \(\beta\) was higher than 1.0. On the other hand, a considerable number of bridges were intact even if \(\beta\) was less than 1.0. The situation is not changed even if buoyancy is considered as shown in Figs.8 and 9. In Figs.7 and 8, the velocity of the tsunami is assumed as a constant value in every bridge. In reality, the velocity is considerably different in each case.
To increase the accuracy of the safety index $\beta$, we tried to estimate the velocity from inundation depth, which was obtained through our surveys as,

$$v = k \sqrt{h}$$

(7)

where $k$ is the coefficient that includes the Froude number, and $h$ is the inundation depth.

To study the appropriate value for the coefficient, frictional resistance calculated by equation (4) and the inundation depth are compared in Fig.10. In this figure, reliable data are carefully selected.

The drag-inundation curves were also indicated by assuming 0.2, 0.4, or 0.6 as coefficients of $k$ from equations (1) and (7). Every intact bridge had a frictional resistance higher than the drag with the coefficient $k$ being 0.2. On the other hand, the frictional resistance of every washed away bridge was less than the drag with the coefficient $k$ being 0.6. When focusing on frictional resistance, every heavy bridge whose frictional resistance exceeded 30 N/mm$^2$ was intact, while every light weight bridge whose frictional resistance was below 5 N/mm$^2$ was washed away.

Through the discussion in Fig.10, we tentatively assumed 0.7 for the coefficient $k$. In Fig.11, which indicates the histogram of the safety index $\beta$, the drag was calculated by assuming 0.7 as the coefficient for $k$. No bridge was washed away if $\beta$ was higher than 1.0. However, a considerable number of bridges were intact even if $\beta$ was small. Equation (7) is a simplified method for the estimation of velocity. There is a possibility that the accuracy, as seen in Fig.11, is increased by using accurate velocity. Tsunami propagation and run-up analysis will provide a more accurate velocity for equation (1). The lift force should also be considered in the damage mechanism in the future.

4. ESTIMATION OF VELOCITY AND HEIGHT OF TSUNAMI BY MOTION PICTURE ANALYSIS

Discussion in the previous section indicates the importance of tsunami wave velocity and wave height to evaluate the tsunami force acting on the bridge girder. Measured data of tsunami wave velocity were very few, but motion pictures by video camera were taken by residents in several places. In this section, Utatsu bridge is examined to determine how the bridge girders fell down using recorded motion pictures.

Utatsu Bridge was a 304-m-long, 8.3-m-wide, 12-span, pre-stressed concrete bridge that consisted of three types of girders. It was located in Minamisanriku -cho in Miyagi prefecture, about 140 km away from the epicenter. Based on the field survey, eight girders were washed away by the tsunami while no pier collapsed (Figs.12 and 13).

The motion pictures by video camera were taken by residents in the Isatomae area of Minamisanriku Town. The start time of the video was around 31 min.
after the occurrence of the earthquake. Analysis of the motion picture can indicate the wave height and velocity of tsunami at certain time points.

As shown in Fig. 14 motion pictures were taken in different places. However, only the tsunami at Spot C near S9 can be observed clearly, so the wave velocity is measured here and the wash-away of girder S9 is analyzed.

The motion picture shows that with the arrival of the tsunami some barges and wreackages of buildings became floating debris and flowed with the tsunami wave. Using Google Earth’s distance measurer and stopwatch, the distance between the two spots and the time span for the floating debris to flow from one spot to the other was obtained. The velocity of debris can be roughly computed by equation (8). This velocity can be regarded as the approximate wave velocity at the video shot location.

\[ v = \frac{l}{t} \]  

Here, \( v \) is the wave velocity (m/s); \( l \) is the distance between the two spots (m); and \( t \) is the time span for debris flowing from one spot to the other (s).

As shown in Fig. 15 the flow velocities of five other pieces of debris are computed (flow distances are plotted in Fig. 16), as shown in Table 2. The average flow velocity of the debris is 3.79 m/s, which is regarded as the wave velocity at S9 at 37.88 min. Afterwards, the average wave velocity at S9 at 39.63 min. is measured as 4.39 m/s. After checking the video, the authors note that the wave height at Spot A and B can be measured (Fig. 14), by contrasting the water level and the height of local structures.

In order to determine the wave height field survey was combined with motion pictures. As shown in Fig. 17 the top of a building is measured as 2.3 m.

![Fig. 13 Location of fallen down girders.](image)

![Fig. 14 Spots of motion pictures taken.](image)

![Fig. 15 Samples of debris for estimation of wave velocity.](image)

![Fig. 16 Measured displacement of debris No.1-6.](image)

![Fig. 17 Top of a building measured as 2.3 m.](image)

| No. | Debris type       | Distance [m] | Time [s] | Velocity [m/s] |
|-----|-------------------|--------------|----------|----------------|
| 1   | Barge             | 2.79         | 1.47     | 1.90           |
| 2   | Barge             | 3.23         | 1.47     | 2.20           |
| 3   | Driftwood         | 5.38         | 1.47     | 3.66           |
| 4   | Black object      | 6.46         | 1.47     | 4.39           |
| 5   | Black object      | 9.15         | 1.47     | 6.22           |
| 6   | Box               | 6.46         | 1.47     | 4.39           |
|     | **Average**       |              |          | **3.79**       |
In the motion picture the building was flooded at 37.37 min. after the earthquake. Then, the water level was estimated to be 3.45 m. At 40.40 min. after the earthquake occurred, the girder top was just submerged. Since the top height of the bridge girder was 8.3 m, the wave height was estimated as 8.3 m. This procedure is able to represent the wave situation around the bridge as shown in Figs. 18 and 19.

Based on the estimated wave situation the horizontal force and the buoyancy can be evaluated.

5. EXPERIMENTAL INVESTIGATION OF TSUNAMI FORCE ACTING ON BRIDGE GIRDER

The bridge girder of Numata overpass located in Rikuzentakada city in Iwate Prefecture was washed out about 20 m by the tsunami. The bridge fall prevention device was installed in this bridge (Fig. 20). Only slight damage was seen on the bridge fall prevention device, and the anchor bars remained vertical and undamaged. In other words, it is hypothesized that the girders were not subjected to strong horizontal force, but that they were first raised by the lift force, and then washed out. Therefore, in this study, experiments and numerical simulations were conducted to clarify the tsunami force and girders outflow mechanism.
(1) Hydraulic experiment

Using a big water channel (10m width, 4m depth, 37m length) owned by the Port and Airport Research Institute, the stability of the bridge girder of Numata overpass was examined. The experimental setup is shown in Figs. 21 and 22.

![Fig.21 Experimental setup.](image)

The scale of the model was 1/10. The experimental parameters are shown in Table 3 in which two types of flow, such as steady flow and flow with solitary wave are chosen. In the steady flow experiments, initial water level is 1.33m to 1.73m and the velocity is 0.7m/s to 2.0m/s. In the solitary wave experiments, initial water level is 1.22m, 1.33m, 1.43m and wave height is 0.2m to 0.5m.

Wave pressure gauges (PG) and pour water pressure gauges (UG) were installed at 40 locations on the front, back, top, and bottom surfaces of the girders on two measurement lines—center line and bridge pier side (130 mm from the end). For the solitary wave experiment, two girders were placed: the one to which measurement instruments were attached was anchored with bolts, and the other was left as it was. For the flow experiment, only one girder anchored with bolts was placed; then, the bolt was removed and the experiment was repeated to confirm whether it was washed out.

Figures 23 and 24 show the snapshots of experiments. In any case of the steady flow experiment, no wash away of girder was observed. On the other hand, the wash away of girders was confirmed in six cases of solitary wave experiment. When the initial water level was 1.22m, the girder moved at a wave height of 0.4m. In the case of initial water level 1.43m, wash away of girder was confirmed in a wave height 0.5m as shown in Fig. 24.

![Fig.23 Snapshot of steady flow experiment.](image)

![Fig.24 Snapshot of solitary wave experiment.](image)
(2) Stability analysis by using experimental data and numerical simulations

Figures 25 and 26 shows the results of both cases of steady flow and solitary wave. The legends in Fig.25 represent cases indicated by the initial water depth. For example, d1.33 refers to the case with initial water depth of 1.33m. Similarly “I.W.D” and “W.H.” in Fig.26 mean initial water depth and wave height, respectively.

It is very interesting that in the case of steady flow with increase of flow velocity, both the horizontal and vertical forces acting on girder increase but the direction of vertical force is downward. This indicates that the increase of flow velocity, the girder sticks to the abutments with increased force.

On the other hand, the uplift force increases with the increase of wave height as well as the increase of horizontal force in the case of solitary wave.

The stability of the bridge girder was calculated in terms of the safety factor for sliding and rotating by comparing the experimental data and the numerical simulation results taken by CADMAS-SURF/3D10).

In steady flow, the force and sliding safety factor ($\beta_x$) were calculated. In the solitary wave, the force acting on the bridge girder and rotation safety factor ($\beta_m$) were calculated. Figures 27 and 28 show the results of the safety factors.

In the case of steady flow, the safety factor $\beta_x$ decreases with the increase of velocity, but in any case it is not less than 1.0. This is because the frictional resistance force of the bridge girder is increased by increased downforce. This explains why the bridge girder did not move under steady flow.

In the case of solitary wave, the safety factor $\beta_m$ decreases with the increase of wave height. The vertical force is decreased due to the differential pressure decrease when the initial water level is higher than the girder crest. The safety factor $\beta_m$ of less than 1.0 indicates that the girder to be moved.
6. MECHANICAL MODEL OF THE FALL DOWN OF BRIDGE GIRDER

In order to simulate the collapse of Utatsu Ohashi bridge, the Applied Element Method is introduced for its advantages of simulating structural progressive collapse\(^{12}\). The AEM is a discrete crack approach, in which elements can be separated, fall and collide to other elements in a fully nonlinear dynamic scheme of computations.

In AEM, structures are modeled with the elements assembled as shown in Figs.29-31. The elements are connected together along their surfaces through a set of normal and shear springs. Those springs are responsible for the transfer of normal and shear stresses among adjacent elements.

Each spring represents stresses and deformations of a certain volume of the material. Every two adjacent elements can be completely separated once the springs connecting them are ruptured.

Fully nonlinear path-dependent constitutive models are adopted. For concrete in compression, elasto-plastic and fracture model is adopted. For tension, linear stress-strain relationship is adopted until cracking. In the discrete crack approach, reinforcing bars are modeled as bare bars.

For modeling the bearings, the interface material is introduced where the material is initially cracked and cannot carry tensile stresses. In compression, linear behavior is assumed up to compression failure. Shear behavior is also linear up to a certain point and is capable of keeping that shear stress as long as normal stresses are not changed. When compressive stresses increase, shear capacities increase unless cracks open or during sliding of girders (See Fig.31).

The AEM is a stiffness-based method in which an overall stiffness matrix is formulated and the equilibrium equations including each of stiffness, mass and damping matrices are nonlinearly solved for the structural deformations (displacements and rotations). The solution for equilibrium equations is an implicit one adopting a dynamic step-by-step integration.

In the AEM, two adjacent elements can separate from each other when the matrix springs connecting them are ruptured. Elements may automatically separate, recontact or contact other elements. In this study, the Extreme Loading for Structures (ELS) software (www.appliedsciencecint.com) is used.

Using AEM code, the collapse mechanism of Utatsu Bridge is simulated. How the tsunami impacted the bridge has been discussed in Chap.4. The fall down of girders is shown in Figs.12 and 13. Overall model is shown in Fig.32 and some examples of structural element models are shown in Figs.33-35.

Fig.29 Constituent element (members).

Fig.30 Constituent element (RC element).

Fig.31 Constituent element (bearing interface).

Fig.32 Overall model of Utatsu Bridge.
A total of 21,430 elements were used for the whole bridge model. Material properties are shown in Table 4.

Hydrodynamic forces can be computed as follows\(^3\),\(^4\):

\[
F_d = \frac{1}{2} \rho_s C_d AV^2 
\]

(9)

where

- \(F_d\) = horizontal drag (hydrodynamic) force
- \(C_d\) = drag coefficient \(\cong 2.0\) (FEMA, 2008)
- \(\rho_s\) = density of sea water including sediments (= 1.2 density of sea water)
- \(V\) = velocity of water
- \(A\) = projected area of structural member normal to flow

Buoyancy is calculated as follows:

\[
F_b = \rho_s g V_D 
\]

(10)

where

- \(F_b\) = buoyancy
- \(V_D\) = volume of water displaced by the submerged object (bridge deck)
- \(\rho_s\) = density of sea water including sediments (= 1.2 density of sea water)
- \(g\) = gravitational acceleration

The buoyancy was considered in the model by reducing the unit weight of the bridge concrete by a magnitude equals to the unit weight of the sea water. Bricker et al.\(^5\) carried out two-dimensional computational fluid dynamic analysis to the deck of Utatsu Ohashi bridge and found out that air was trapped between girders during the motion of water. This trapped air causes additional buoyancy that was considered essential in the analysis. The magnitude of those additional buoyancy was equal to the weight of the volume of water displaced by the trapped air and was calculated as follows:

\[
F_{bT} = \rho_s g V_{AT} 
\]

(11)

where

- \(F_{bT}\) = buoyancy due to trapped air
- \(V_{AT}\) = volume of water displaced by the trapped air
- \(\rho_s\) = density of sea water including sediments (= 1.2 density of sea water)
- \(g\) = gravitational acceleration

![Fig.33 Model of girder.](image)

![Fig.34 Model of pier head.](image)

![Fig.35 Mesh discretization for pier and girder.](image)

| Table 4 Material properties (MPa). |
|------------------------------------|
| **Young’s modulus**               |
| Concrete                          |
| Steel and RC bars                 |
| Bearing interface                 |
| Compressive strength              |
| 2.67E4                            |
| 2.03E5                            |
| 2.03E5                            |
| Tensile strength                  |
| 30                                |
| -                                 |
| 1500                              |
| Yield strength                    |
| 2                                 |
| -                                 |
| 0                                 |
| Ultimate strength                 |
| -                                 |
| 360                               |
| -                                 |
Water velocity, water direction, and water height for the whole bays of the bridge were taken from the calculations of Fu et al.\(^9\). **Figure 36** shows the collapse simulation result by AEM. Compared with **Fig.13**, AEM was proven to be a good tool to simulate the collapse mechanism of bridges.

### 7. CONCLUSION

The research work covers the field survey of damage of bridges by the tsunami on March 11, 2011, the damage analysis based on database, tsunami characteristic after hitting land surface, the hydraulic experiment with development of numerical simulation technique, and the application of Applied Element Method to simulate the collapse of bridge girders. The following considerations are derived:

1. Internet media is a powerful tool to survey the damage by tsunami in a wide area.
2. More than 200 out of 1793 bridges in the inundation area of East Japan (Tohoku region) were washed away by the tsunami. Comparing the surviving bridge girders with the ones that were washed away, girders with rather shallow cross sections are observed to be more resistive against tsunami.
3. A safety factor (\(\beta\)) against drag was calculated according to Kosa’s equation. To increase the accuracy of prediction, accurate velocity is required and lift force should be considered. Water pressure acting on bridge girder may be evaluated by proposed \(\beta\) value. The location of the bridge and the height of the pier might influence the condition of girder when the tsunami hits.
4. The analysis of motion pictures gives a lot of important information on the characteristics of the tsunami. Such information can be good in deces for developing simulation techniques for the tsunami and tsunami force action on bridge structures.
5. Experimental examination reveals that a solitary wave produces up-lift force on a bridge girder. On the other hand, uniform flow eventually causes force to push a girder to abutments.
6. The experiment reproducibility analysis performed using CADMAS-SURF/3D confirmed that the wave pressure was high on the front surface and above the bridge girder, but this conformed closely inside the bridge girder. A future challenge is to clarify how the tsunami scale and lift force are related to the width and thickness of bridge girders.
7. Applied Element Method was successfully used to simulate the collapse of the Utatsu Ohashi bridge. The amount of trapped air between deck girders during the tsunami had a significant effect on the behavior of the bridge due to the buoyant force accompanied by the trapped air.

**ACKNOWLEDGMENT:** The authors greatly appreciate the funding received from the Grant-in-Aid for Scientific Research (A) 24246079 “Proposal for methods of clarifying the mechanism of bridge girder washed out by giant tsunamis and of verifying countermeasures” (Representative: Maruyama Kyuichi, Nagaoka University of Technology).

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(Received October 6, 2016)