Evaluation of Tsunami Scouring on Subsea Pipelines

R. Komata

1 Tokyo Gas Co. Ltd., Yokohama, Japan
E-mail: komata@tokyo-gas.co.jp

Abstract. It is important that subsea pipelines are designed and maintained to withstand earthquakes and tsunamis, especially in earthquake-prone regions such as Japan. Tsunami scouring of the seabed may reduce the amount of soil covering a subsea pipeline, exposing it to harmful wave action. In this study, we investigated the feasibility of a subsea pipeline by calculating the tsunami scouring volume for representative tsunamis via numerical analysis. As a case study, we determined how subsea pipelines in the Kashima-nada sea area, Japan, would be affected. The results obtained indicate that for both a level 2 tsunami and a level 1 tsunami, scouring does not significantly affect the pipeline and no construction is subsequently required to restore the soil cover.

1. Introduction

Japan is in an earthquake-prone region; hence, it is vital that gas pipelines in this region are designed and maintained to withstand earthquakes. Japan has constructed onshore pipelines that are designed to be aseismic in the case of earthquakes and ground displacement due to liquefaction. However, subsea gas pipelines constructed in the open ocean must be designed to also withstand tsunami action. There are two types of subsea pipelines: (1) pipelines constructed in trenches and buried with backfill sand to protect against damage from anchors and wave forces and (2) pipelines placed directly on the seabed. Buried pipelines can be impacted by tsunamis in many ways however one of the most common impacts is pipeline exposure due to sediment scouring. Once the pipeline becomes exposed it is at risk of anchor strikes, and deformation and vibration damage due to wave action.

It is assumed that the extent of tsunami driven sediment scouring depends on the size of the tsunami; hence, the effects on subsea pipelines differ in the scale of the tsunami scour. Thus, it is estimated that the durability of the subsea pipeline differs according to the scale of the tsunami. Furthermore, the Japanese government has proposed that tsunami disaster prevention should change to reflect the scale of the threat (i.e., the potential size of the tsunami) that exists in Japan. Therefore, in this study we examined two types of tsunamis, a large-scale low-frequency tsunami and a small-scale high-frequency tsunami, and calculated the depth of seabed sediment transported by each event. The effects of tsunami-driven scouring on subsea gas pipelines placed in the Ibaraki area were then determined.

2. Representative tsunamis and pipeline performance requirements

Currently, no standards or design guidelines exist, in Japan or abroad, for safety checks related to tsunami scouring of pipelines on the ocean floor. Therefore, to determine the effects of tsunami scouring on subsea pipelines, we referred to the earthquake resistance design guidelines for high-pressure gas pipelines on land [1] and a survey on tsunami disaster prevention in order to select representative tsunamis and propose performance requirements for subsea pipelines.
The current guidelines adopt a two-step design procedure, as shown in the Proposal on Earthquake Resistance for Civil Engineering Structures [2]. In this design, level 1 earthquake motion is defined as an earthquake event whose occurrence probability one to two times within the service period, and level 2 earthquake motion is defined as an earthquake whose occurrence probability is very low but that occurs close to a fault and impact is extremely strong. The steps of this method comprehensively determine pipeline performance requirements according to the importance of the structure and its influence at the time of the disaster. According to the earthquake resistance design guidelines for high-pressure gas pipelines, after a level 1 earthquake, the gas pipelines should not require repairs and should continue to function without problems. After a level 2 earthquake, the gas pipelines may deform but should not leak gas (Table 1).

For the representative tsunamis, proposals such as the "Special investigation meeting on earthquake and tsunami countermeasures based on the 2011 Tohoku tsunami lessons" [3] are referred to in the design of the structural and evacuation plan. In the investigation, tsunamis are divided into two classes: large-scale tsunamis (level 2) that occur with very low frequency but can cause an extremely large amount of damage and small-scale tsunamis (level 1) that occur with high frequency but do not produce high wave levels or cause excessive damage. The structural performance requirements are determined for each tsunami type individually.

Thus, based on these earthquake resistance design guidelines for high-pressure gas pipelines and recommendations on tsunami disaster prevention, in this study, we determined the pipeline performance requirements and selected representative tsunamis for evaluation as shown in Table 2. Because the pipelines are installed in a trench on the ocean floor to minimize the risk of damage due to ship anchors and fishery activities, the performance requirements for the level 1 tsunami specify that the soil covering the pipeline should not necessitate restoration after scouring. For a level 2 tsunami, the performance requirement is that the pipeline should not be exposed by tsunami scouring. Although leakage will not occur immediately if the pipeline is exposed after a level 2 tsunami, harmful deformation may occur owing to the tsunami wave force, therefore, we determine these conditions to ensure pipeline safety. The representative tsunamis used in this study are detailed in Sections 5.1.2 and 5.2.2.

### Table 1. Performance requirements of a pipeline based on the earthquake resistance design guidelines for high-pressure gas pipelines.

| Representative earthquake | Performance requirement |
|----------------------------|-------------------------|
| Level 1 earthquake         | Probability of occurrence 1–2 times within the service period  |
|                            | Gas pipelines should not require repair and should function without problems |
| Level 2 earthquake         | Very low probability but occurs close to the fault and has an extremely strong impact  |
|                            | Gas pipelines may deform but may not leak gas |

### Table 2. Performance requirements of a pipeline and tsunami levels determined in this study.

| Representative tsunami | Performance requirement |
|------------------------|-------------------------|
| Level 1 tsunami        | High frequency of occurrence but does not produce high wave levels  |
|                        | No work needed to restore the soil cover after scouring |
| Level 2 tsunami        | Very low frequency of occurrence but could cause excessive damage  |
|                        | Pipelines should not be exposed after tsunami scouring |

### 3. Overview of the numerical model for tsunami sediment transport

In this study, we used a numerical model presented by Takahashi et al. [4] to gage sediment transport due to tsunami. The model was developed to reproduce the changes in the seabed observed at Kesennuma bay, Japan, based on the Chilean tsunami of 1960 (Figure 1).
As shown in Figure 2, we first calculated the tsunami height and then the sediment transport using the tsunami height. By repeating this procedure for each analysis step, the time series for tsunami sediment scouring was estimated.

Tsunami flux flow calculation is a general method for calculating the differential nonlinear long-wave motion equation composed of the continuity equation (equation (1)) and the momentum conservation equation (equation (2)):

\[
\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0
\]  

\[
\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{gN^2}{D^2} M \sqrt{M^2 + N^2} = 0
\]

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{gM^2}{D^2} N \sqrt{M^2 + N^2} = 0
\]

where \( t \) is time, \( x \) and \( y \) are the horizontal position coordinates, \( D \) is the depth \((D = h + \eta, \text{where } h \text{ is the seabed, and } \eta \text{ is the sea surface})\), \( g \) is the gravitational acceleration, \( n \) is the Manning roughness coefficient, and \( M \) and \( N \) are the flow flux in the \( x \) and \( y \) directions, which are calculated by integrating the horizontal flow velocities \( u \) and \( v \) from the seabed to the sea surface. The sediment transport calculation is composed of the continuous equation of the bed load layer (equation (3)) and the continuous equation of the suspended load layer (equation (4)):

\[
\frac{\partial Z}{\partial t} + \frac{1}{1 - \lambda} \left( \frac{\partial Q_s}{\partial x} + \frac{\partial Q_s}{\partial y} + w_{ex} \right) = 0
\]

\[
\frac{\partial C_s, M}{\partial x} + \frac{\partial C_s, N}{\partial y} + w_{ex} + \frac{\partial C_s, h_s}{\partial t} = 0
\]

where \( Z \) is the bed level and \( \lambda \) is the porosity, \( Q_s \) and \( Q_v \) are the bed load rates in the \( x \) and \( y \) directions, \( C_s \) is the mean concentration of the suspended load, \( h_s \) is the depth of the load layer, and \( w_{ex} \) is the exchange load rate between the suspended and bed load layers are calculated using equations (5) and (6) obtained from the hydraulic experiment of Takahashi et al. [4]:

\[
Q = 21 \sqrt{sgd} \tau_s^{3/2} \quad Q_s = \frac{MQ}{\sqrt{M^2 + N^2}} + \epsilon_s \left| \frac{\partial h}{\partial x} \right| \quad Q_v = \frac{NQ}{\sqrt{M^2 + N^2}} + \epsilon_s \left| \frac{\partial h}{\partial y} \right|
\]

\[
w_{ex} = 0.012 \sqrt{sgd} \tau_s^{3/2} - w_{ex} C_s
\]

where \( s \) is the specific gravity of water \((= \rho / \sigma - 1; \rho \text{ is the sea water density and } \sigma \text{ is the sand density})\), \( \tau_s \) is the critical Shields number, \( \epsilon_s \) is the vertical diffusion coefficient, and \( w_{ex} \) is the settling velocity. The Shields number is the non-dimensional rate of bed load transport limit (limit sweeping power), which is expressed by equation (7):

\[
\tau_s = \frac{u_{\tau}}{\sqrt{\left( \frac{\sigma}{\rho} - 1 \right) g d}}
\]

where \( u_{\tau} \) is the critical friction velocity. In the case of sand, the critical Shields coefficient is 0.034–0.05 from Iwagaki et al. [5].
Figure 1. Sediment transportation model. [4]

4. Validation of the numerical model and material parameters

4.1. Conditions
Previous studies [6] have confirmed that the numerical analysis method used in this study has adequate validity for determining sediment transport resulting from tsunamis. However, there is no established method for setting data related to the target area of the numerical analysis, such as, the boundary conditions, water level, and altitude; hence, it is necessary to confirm their validities beforehand. Therefore, we used the data from the 2011 Tohoku Tsunami to calculate tsunami propagation for the Kashima Nada area, and compared observation records and conditions to confirm the validity of the results obtained. However, because the changes in seabed topography during the 2011 Tohoku tsunami are still being analyzed, our calculation results for sediment transport were not compared with available observations.

As shown in Figure 3, the calculation of tsunami propagation involved a sea area including the Kashima-Nada measuring an area of 1,458 km × 1,239 km. As shown in Table 3, terrain data such as water depth and altitude of the target area were the same as those adopted in the Ibaraki coastal tsunami flooded area study report [7]. The earthquake faulting of the Tohoku tsunami was the same as the model adopted by the Study Group on the Cabinet Office's Great Earthquake [8], and the initial vertical seabed displacement due to fault data and fault movement are shown in Table 4 and Figure 4, respectively.

As the calculation of tsunami propagation utilizes the difference method, it is necessary to divide the target region into computation lattices of appropriate sizes. In this study, the region was divided into a calculation lattice from a maximum of 2,160 m to a minimum of 40 m, considering the trade-off
between computation time and accuracy (Figure 3). Land side and offshore side boundary conditions were assumed to be under perfect reflection and free transmission conditions, respectively, and the tide level was set as T.P. - 0.52 m at the time of the occurrence of the Tohoku tsunami. The calculation interval was 0.2 s, and the calculation duration was 6 h from the fault movement.

Figure 3. Location map of the study area (showing entire area and nested calculation area).

Figure 4. Initial vertical seabed displacement for Tohoku earthquake.

Table 3. Material parameters for validation of the numerical model.

| Index                        | Calculation conditions                                                                 |
|------------------------------|---------------------------------------------------------------------------------------|
| Calculation method           | Model sediment transport from Takahashi et al. (1999) [4]                             |
| Calculation area             | Spatial difference: Staggered grid                                                   |
|                              | Temporal difference: Leapfrog integration                                            |
| Calculation mesh spacing     | Plane Cartesian coordinate system No.9                                               |
| Number of meshes             | 2,160 m→720 m→240 m→120 m→40 m                                                        |
| Terrain data                 | Based on the survey report from the central disaster prevention council and Ibaraki coastal tsunami inundation area |
| Fault model                  | Tohoku Region Pacific Offshore Earthquake Cabinet Office model (2012) [8]             |
| Ground displacement          | Method of Okada (1992) [9]                                                            |
| Initial condition            | Provide the above ground variation amount with respect to the sea level T.P.-0.52 m |
| Initial tide level           | Free transmission condition                                                          |
| Boundary condition (coast side) | Perfect reflection condition                                                        |
| Boundary condition (land side) |                                                                                     |
| Calculation time             | 6 h                                                                                   |
| Calculation time interval    | 0.2 s                                                                                  |
Table 4. Conditions of the Tohoku tsunami fault.

| Parameter                  | Value          |
|----------------------------|----------------|
| Occurrence year            | 2011           |
| Magnitude                  | 8.2            |
| Epicenter                  | Latitude: 34.84|
|                            | Longitude: 139.76|
| Number of fault elements   | 4,575          |
| Fault area (km²)           | 119,974        |
| Depth 0–10 km              | 6.50           |
| Depth 10–16 km             | 13.81          |
| Depth 16–32 km             | 11.81          |
| Depth over 32 km           | 2.78           |

4.2. Results and comparison with observed tsunami height

Figure 5 shows the maximum wave height distribution over the entire calculation period of tsunami propagation. The maximum wave height is larger in coastal areas than in offshore areas by approximately 4 m. In addition, because the maximum wave height distribution cannot be explained only by the distance from the fault, located to the northeast of the calculation area, it is inferred that the water depth, altitude, shape of the coastline, etc., also have a large effect. Figure 6 shows the time histories of wave heights at the P1, P2, and P3 points along the coast. The period of the tsunami was approximately 30 min, and it was confirmed that a large amplitude tsunami approached several times.

The Tohoku tsunami Joint Study Group gathered a wide range of experts to contribute to the reconstruction plan of the disaster area, a future disaster prevention plan, and reconsideration of the tsunami disaster prevention plans for other tsunami prone areas [10]. Here, we compared our calculation results with the results of field surveys conducted by this group. Figure 7 compares the maximum calculated wave height with time and the trace height of the tsunami obtained by field survey for all 60 points along the coast. For some points, although the calculation result and field survey result showed a deviation of approximately 1.5 m, they generally showed the same pattern. For all 60 sites, we obtained the maximum tsunami height from both the calculation and field survey using the $K$ and $\kappa$ indices proposed by Aida et al. [11] as described in equations (8) and (9). We quantitatively evaluated the spatial fitness of the tsunami trace height:

$$\log K = \frac{1}{n} \sum_{i=1}^{n} \log K_i$$

$$\log \kappa = \left[ \frac{1}{n} \left( \sum_{i=1}^{n} (\log K_i)^2 - n(\log K)^2 \right) \right]^{1/2}$$

where $n$ is the number of points where the trace height of the tsunami is compared, and $K$ is the height of the tsunami trace obtained by the field survey for numerical analysis results at each site. The evaluation results using the index of Aida et al. are shown in Table 5. The geometric mean, $K$, shows the average correspondence between the height of the tsunami trace height and the calculated value when it is closer to “1”; the calculated value thus corresponds well with the tsunami trace height. The geometric standard deviation shows the variation in correspondence between the tsunami trace and the calculated value; the smaller the geometric standard deviation, the better the calculated value corresponds to the tsunami trace height. $K$ and $\kappa$ are 1.1 and 1.3, respectively, and range from 0.8 to 1.2, which is generally considered to indicate adequate compatibility, as indicated in the guidance on
tsunami river run-up analysis [12]. Therefore, according to spatial fitness, the calculation result and the results of the field surveys correspond well. As shown above, the 2011 Tohoku tsunami propagation was calculated, and consistency between the calculation and observation results was confirmed; therefore, the target area of numerical analysis, boundary conditions, water level, and altitude data are considered to be valid.

**Figure 5.** Modeled maximum height for Tohoku tsunami.

**Figure 6.** Time histories of wave heights at the P1, P2, and P3 points along the coast. Contours and color map show seabed altitudes.

**Figure 7.** Comparison of recorded wave height and modeled wave height.

**Table 5.** Validation of tsunami height using the Aida method.

| Index                              | Result | Required range |
|------------------------------------|--------|----------------|
| Geometric mean (K)                 | 1.06   | 0.8<K<1.2      |
| Geometric standard deviation (κ)   | 1.29   | κ<1.6          |

5. **Analysis of tsunami scouring and pipeline evaluation**

5.1. **Large-scale and low-frequency tsunamis (Level 2 tsunamis)**

5.1.1. **Conditions.** The entire tsunami propagation area for the scouring calculation described in Section 4.2 would result in a large-scale numerical analysis; therefore, the calculation area is reduced with the smallest calculation lattice being 40 m, as shown in Figure 3. In addition, the input boundary condition is a tsunami level waveform at multiple points, and interpolation is performed between each point in a linear manner. The Manning roughness coefficient was 0.025 [13], the sediment grain size was 0.2 mm, porosity was 0.4 [14], and the saturated suspended sediment concentration was 1 % [15].
5.1.2. Tsunami selection and outline. Based on the Ibaraki Coastal Tsunami Inundation Forecast Area Report conducted by Ibaraki tsunami disaster prevention measure study, we selected the Tohoku tsunami and Empo-boso-oki tsunami as level 2 tsunamis. The Cabinet Office fault model [16] used in Section 4.1 was used for the Tohoku tsunami. This model for Empo-boso-oki tsunami, which describes the largest class of tsunami magnitude (Mt 8.6–9.0) proposed by the earthquake research promotion headquarters, was adjusted to 1.5 times the slip amount of the model. Table 6 and Figure 8 show the initial displacement amounts in the vertical direction of the seabed ground accompanying fault data and fault movement, respectively.

**Table 6. Conditions of the Empo-boso-oki tsunami fault.**

| Occurrence year | 1677 |
|----------------|------|
| Magnitude      | 8.8  |
| Epicenter      | Latitude: 40.31 |
|                | Longitude: 144.40 |
| Number of fault elements | 972 |
| Fault area (km²) | 26,118 |
| Depth 0–10 km | 5.00 |
| Depth 10–16 km | 5.42 |
| Depth 16–32 km | 7.04 |
| Depth over 32 km | 6.78 |

**Figure 8. Initial vertical seabed displacement for Empo-bosooki earthquake.**

5.1.3. Model results. For the Tohoku tsunami and the Empo-boso-oki tsunami, the tsunami propagation calculations and sediment transport calculations were performed with time from the occurrence of the tsunami until convergence, revealing topographical changes due to the sediment movement. The Tohoku tsunami showed larger topographical changes (Figure 9). Approximately 0.5–0.6 m of sediment was transported from the coast to an offshore area of approximately 40 m depth 1 h after the first wave of the tsunami arrived. Thereafter, accumulation occurred in the scoured area over time and sand was gradually re-buried. The final topographical change in this area was approximately -0.1–0.3 m 6 h after the tsunami converged. At the periphery of the structure such as breakwaters in the coastal area, large amounts of sand were locally transported 1 h after the tsunami occurred and deposition began after another 3 h. This trend continued after 6 h, indicating a different behavior to that offshore. Figure 10 shows the maximum amount of scouring and deposition from tsunami occurrence up to 6 h after the tsunami.

Figure 11 shows the maximum amount of scouring and sedimentation for the Empo-boso-oki tsunami and the final topography changes 6 h after the tsunami. As with the Tohoku tsunami, large sediment scouring occurred from the coastal area to an offshore area of approximately 40 m depth, with a maximum scoured amount of 0.5 m. Local scouring and sedimentation in the surrounding areas were also confirmed in the periphery of the coastal area and with the same tendency as the Tohoku tsunami. As the majority of the areas where the subsea pipeline may be laid have water depths ranging from 20–40 m in general, the maximum scouring volume, amount of deposition, and final landform changes
for the entire area are shown in Table 7. The maximum scouring amount for the Tohoku and Empo-
oboso-oki tsunami was 0.6 m and 0.4 m, respectively. By assuming 1.8 m of sand cover, which is
commonly used when laying land-based high-pressure gas pipelines, we confirmed that the modeled
scouring amount was much lower than this, and would not expose the subsea pipeline.
Therefore, we confirmed that the performance requirements set in this study were met. Although more
scouring occurred in the periphery of the structures such as breakwaters in the coastal area than in the
offshore area, considering that the influence of sedimentation in the coastal area, would likely increase
the amount of sand covering, lay the pipeline can be laid avoiding these areas; thus, such large
scouring should not be problematic.

Figure 9. Temporal variation of modeled topographical change: 30 min, 1h, 2h, 3h, 4h, and
6h after Tohoku tsunami.

Figure 10. Modeled maximum net erosion and deposition for Tohoku tsunami. Contours are seabed altitudes.
Figure 11. Modeled maximum net erosion, deposition, and final topography change for Empo-boso-oki tsunami. Contours are seabed altitudes.

Table 7. Modeled maximum net erosion, deposition, and final topography change for level 2 tsunamis at shallower depths of 20 m (except around structures).

| Tsunami       | Maximum scouring (m) | Maximum sediment deposition (m) | Final topography change (m) |
|---------------|-----------------------|---------------------------------|-----------------------------|
| Tohoku        | 0.6                   | 0.5                             | -0.1–0.3                    |
| Empo-boso-oki | 0.5                   | 0.4                             | -0.4–0.2                    |

5.2. Small-scale and high-frequency tsunamis (Level 1 tsunamis)

5.2.1. Conditions. As described in Section 5.1, calculations were made for the smallest grid size of 40 m, as shown in Figure 3. The input boundary condition was a tsunami level waveform at multiple points, and interpolation was performed between each point by linear interpolation. The same values as in Section 5.1 were used for the roughness coefficient, particle diameter of the seabed, porosity, and saturated floating sand concentration.

5.2.2. Tsunami selection and outline. The Chilean earthquake tsunami, Genroku earthquake tsunami, Meiji sanriku earthquake tsunami, Miyagi-oki earthquake tsunami and Fukushima-east-oki earthquake tsunami were selected based on the Ibaraki Coast Tsunami Inundation Area Forecast. For the fault model, the Chilean tsunami used the Takaoka model [17], the Genroki tsunami used the Kasahara model [18], the Meiji sanriku tsunami used the Tanioka model [19], the Miyagi tsunami used the Aida model [20], and the Fukushima east-oki tsunami used the Abe model [21]. Figures 12 and 13 and Table 8 show the initial displacement amounts in the vertical direction of the seabed ground accompanying fault data and fault movement, respectively.

The Chilean tsunami was a distant tsunami that propagated over long distances from the Chilean coast to the Japanese coast. For this reason, it is necessary to calculate a tsunami propagation from the Chilean coast to the Japanese coast using a global model of the polar coordinate system and then calculate tsunami propagation of the planar orthogonal coordinate system covering Japan's ocean area [22]. In this study, the calculation in the plane orthogonal coordinate system was conducted using the tsunami propagation calculation results obtained from the global model employed in the Ibaraki Coastal Tsunami Inundation Area Forecast.
Table 8. Condition for each representative earthquake fault. (D is depth; θ is strike angle; δ is dip angle; λ is rake angle; L is length; W is width; U is slip amount; µ is elastic modulus.)

| Tsunami name          | Occurrence year | Magnitude | Latitude | Longitude | D (km) | θ (deg) | δ (deg) | λ (deg) | L (km) | W (km) | U (m) | µ (10^11 dyne/cm²) |
|-----------------------|-----------------|-----------|----------|-----------|--------|---------|---------|---------|--------|--------|------|------------------|
| Chile                 | 1960            | 9.5       | 38.29    | 73.05     | 1      | 10      | 10      | 90      | 800    | 55     | 6.7  | -                |
| Genroku               | 1703            | 8.2       | 34.84    | 139.76    | 0      | 315     | 30      | 153     | 85     | 55     | 6.7  | 3.5              |
| Meiji sanriku         | 1896            | 8.5       | 40.31    | 144.40    | 0      | 190     | 20      | 90      | 210    | 50     | 10.6 | 3.5              |
| Miyagi oki            | 1978            | 7.4       | 38.39    | 142.37    | 25     | 190     | 20      | 76      | 26     | 65     | 2.0  | 7.0              |
| Fukushima east oki    | 1938            | 7.5       | 36.93    | 142.05    | 20     | 200     | 10      | 95      | 100    | 60     | 2.3  | 5.0              |

Figure 12. Initial vertical seabed displacement for Chilean earthquake.

Figure 13. Initial vertical seabed displacement for each earthquake.

5.2.3. Model results. As in Section 5.2.2, tsunami propagation calculations and sediment transportation calculations were performed for the five tsunamis from tsunami occurrence until convergence after 6 h. Figure 14 shows the maximum scouring volume and Table 9 shows the maximum scouring volume, maximum deposition volume, and the final topographical change after 6 h. The maximum scouring volume of the Chilean tsunami was approximately 0.05 m in the coastal area at a depth of ≤ 10 m and approximately 0.03 to 0.04 m in the area where the subsea pipeline may be laid at a depth of 20 m or more. The maximum scouring volume of the Genroku tsunami was 0.04–0.05 m at a water depth of ≤ 10 m and 0.02–0.03 m at a water depth of ≥ 20 m. The maximum scouring volume of the Meiji sanriku tsunami was approximately 0.05 m at a depth of ≤ 10 m but ≤ 0.01 m at a water depth of ≥ 20
m, resulting in minimal scouring. The maximum scouring volume of the Miyagi oki tsunami was \( \leq 0.01 \) m for the entire study area; almost no tsunami scouring occurred. The maximum scouring volume of the Fukushima east-oki tsunami was 0.01–0.02 m at a depth of \( \leq 20 \) m, excluding the peripheral structure, indicating almost no tsunami scouring. Therefore, level 1 tsunamis resulted in maximum tsunami scouring of approximately 0.05 m. Thus, even when sand coverage of the subsea pipeline is reduced by tsunami scouring, it is sufficient for measures such as anchor protection and does not require restoration, thereby meeting the performance requirements of the pipeline.

**Figure 14.** Modeled maximum net erosion for each level 1 tsunami. Contours are seabed altitudes.

**Table 9.** Modeled maximum net erosion, deposition, and final topography change for level 1 tsunamis at shallower depths of 20 m (except around structures).

| Tsunami             | Maximum scouring (m) | Maximum sediment deposition (m) | Final topography change (m) |
|---------------------|-----------------------|---------------------------------|----------------------------|
| Chile               | 0.03–0.04             | 0.03–0.04                       | 0.03–0.04                  |
| Genroku             | 0.03                  | 0.02–0.03                       | 0.01–0.02                  |
| Meiji sanriku       | \( \leq 0.01 \)       | \( \leq 0.01 \)                 | \( \leq 0.01 \)            |
| Miyagi-oki          | \( \leq 0.01 \)       | \( \leq 0.01 \)                 | \( \leq 0.01 \)            |
| Fukushima east-oki  | 0.01–0.02             | \( \leq 0.01 \)                 | \( \leq 0.01 \)            |
6. Conclusion
In this study, the influence of tsunami scouring caused by representative earthquakes for a proposed pipeline off the coast of Ibaraki prefecture was confirmed by numerical analysis. With regard to the assumed tsunami, we set two levels from the viewpoint of the scale of the tsunami and the frequency of occurrence, with reference to the guidelines that set the policies for tsunami countermeasures and high-pressure gas pipeline earthquake design guidelines. The results obtained by numerical analysis are as follows.
For a level 2 tsunami, although tsunami scouring occurs, the scouring volume is lower than the soil covering amount, so the subsea pipeline is not exposed, and it was confirmed that it meets the performance requirement set in this research. Further, for a level 1 tsunami, the tsunami scouring is at most 0.05 m, and even when the coverage of the subsea pipeline decreases due to the tsunami scouring, the soil covering necessary for measures such as anchoring from the ship is sufficient. We confirmed that it meets the performance requirement that it is secured and no construction is required to restore the soil cover after the earthquake.

7. References
[1] The Japan Gas Association, 2003, Earthquake Resistance Design Guidelines for High-pressure Gas Pipelines, JGA(G) 206-03. (in Japanese)
[2] Japan Society of Civil Engineers, 1996, Proposal on Earthquake Resistance for Civil Engineering Structures. (in Japanese)
[3] Disaster Management in Japan from Cabinet Office Japan, 2011, Report of the Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the “2011 off the Pacific coast of Tohoku Earthquake.
[4] Takahashi T, Shuto N, Imamura F, and Asai D 2000 Modeling sediment transport due to tsunamis with exchange rate between bed load layer and suspended load layer International Conference of Coastal Engineering, 27 1508
[5] Iwagaki Y 1956 Hydrodynamical Study on Critical Tractive Force Journal of JSCE 41 1
[6] Kondo T, Morimoto T, Fujimoto N, Tonomo K, and Shikata T 2012 Accuracy Evaluation of Numerical Simulation to Calculate Sediment Transport in Harbor due to Tsunami Proceedings of Coastal Engineering JSCE 68 No.2 396
[7] Ibaraki Prefectural Government, Japan, 2012, Study report of Ibaraki coastal tsunami flooded area. (in Japanese)
[8] Disaster Management in Japan from Cabinet Office Japan, 2012, The reference report of the 12th meeting of the study meeting of the huge earthquake model of the Nankai Trough. (in Japanese)
[9] Okada Y 1992 Internal deformation due to shear and tensile faults in a half-space Bulletin of the Seismological Society of America 82 No.2 1018
[10] The 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group, 2014, Investigation report on Tohoku district Pacific coast tsunami.
[11] Aida I 1978 Reliability of a tsunami source model derived from fault parameters Journal of Physics of the Earth 26 57
[12] National Research Institute for Homeland Technology, 2007, Guidance for analyzing the upstream river of Tsunami. (in Japanese)
[13] Kotani M, Imamura F, and Shuto N, 1998 Tsunami run-up simulation and damage estimation by using GIS Proceedings of Coastal Engineering JSCE 45 356
[14] Fujii N, Oomori M, Takao M, Kanayama S, and Ootani H, 1998 On the deformation of the sea bottom topography due to Tsunami, Proceedings of Coastal Engineering JSCE 45 376 (in Japanese)
[15] Morishita Y and Takahashi T 2014 Accuracy improvement of movable bed model for tsunamis by applying for Kesennuma bay when the 2011 Tohoku tsunami arrived Journal of JSCE 70 No.2 491
[16] The headquarters for earthquake research promotion, 2011, Long-Term Evaluation of Seismic Activity from off Sanriku to Boso oki (Second Edition). (in Japanese)
[17] Takaoka K, Ban K, and Yamaki S 2001 Possibility for prediction of far-field tsunami by numerical simulation Tsunami Engineering Technical Report 18 113 (in Japanese)

[18] Kasahara K, Yamada J, and Ando M 1973 Crustal movements in the southern Kanto district, and a related working hypothesis Publications for the 50th anniversary of the Great Kanto earthquake, 1923, Earthquake Research Institute, University of Tokyo 103 (in Japanese)

[19] Tanioka Y 1996 Fault parameters of the 1896 Sanriku tsunami earthquake estimated from tsunami numerical modeling Geophysical research letters 23(13) 1549

[20] Aida I 1978 Numerical experiments for the tsunami accompanying the Miyagikenoki earthquake of 1978 BERI 53 4 1167

[21] Abe K 1977 Tectonic implications of the large shioya-oki earthquakes of 1938 Tectonophysics 41(4) 269

[22] Imamura F, Nagano O, Goto T, and Shuto N 1987 Trans-oceanic tsunami propagation computation for the 1960 Chilean tsunami Proceedings of Coastal Engineering 34 172

Acknowledgments
We wish to thank Prof. Takahashi from Kansai University for his expert advices. This research was supported in terms of data analysis and numerical modeling by Hydro Technology Institute Co., Ltd.