Construction of a coastal levee in Natsui District, Fukushima Prefecture using trapezoidal CSG dam technology

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ABSTRACT

The coastal area of Fukushima Prefecture suffered enormous damage from the tsunami caused by the 2011 off the Pacific coast of Tohoku Earthquake, and most of the coastal levees were damaged catastrophically. Completed in October 2013, Natsui District Coast was the first coastal levee to be constructed in Fukushima Prefecture as a restoration and reconstruction project. The length of the coastal levee is 920 m, and the crest height (TP; Tokyo Peil) is 7.2 m. The levee volume is 60,000 m3, and 40,000 m3 of that is made using CSG (Cemented Sand and Gravel), which was made with concrete debris from the earthquake together with cement and water. This is the world's first application of the design and construction method of trapezoidal CSG dams to a coastal levee. By adopting this method, not only does it have a "persistent" structure toward overflows of sea wave, but both material cost and disposal cost were reduced by using concrete debris from the earthquake, which has to be handled as general waste. In addition, we were able to greatly shorten the construction period: it took about seven months to complete the main part of the coastal levee.

1. INTRODUCTION

In Japan, the crest height of coastal levees is the sum of the design high tide level and the required height for the design wave and the freeboard [H2]. On the other hand, the height of coastal levees for tsunami is set by each region based on the height of regularly occurring tsunami (once every few decades or over a hundred years) [H1] (Water and Disaster Management Bureau 2011). The coastal levees at Natsui Coast and its vicinity have adopted either the water level of the design tsunami height [H2] or the water level of the design high tide and storm surges [H1], whichever is higher. As a result, the crest height is set to TP+7.2 m based on the water level of [H2] (Iwaki Construction Office 2013).Tsunami occurring on the magnitude of the 2011 Earthquake off the Pacific coast of Tohoku (March 11, 2011) will overflow this coastal levee since the crest height is set to TP+7.2 m. For this reason, the maintenance policy for the Natsui coastal levee was to build “coastal levees with persistent structure” which is not likely to erode even if the tsunami overtops the levees. So, the technology of trapezoidal CSG dam was applied to this levee. CSG is made by mixing cement and water with rocky materials using conventional mixer. CSG is used for the body of trapezoidal CSG dam and preserved the required strength for the permanent structure. The location and view of the Natsui coastal levee are shown in Figure 1, and the specifications are shown in Table 1.

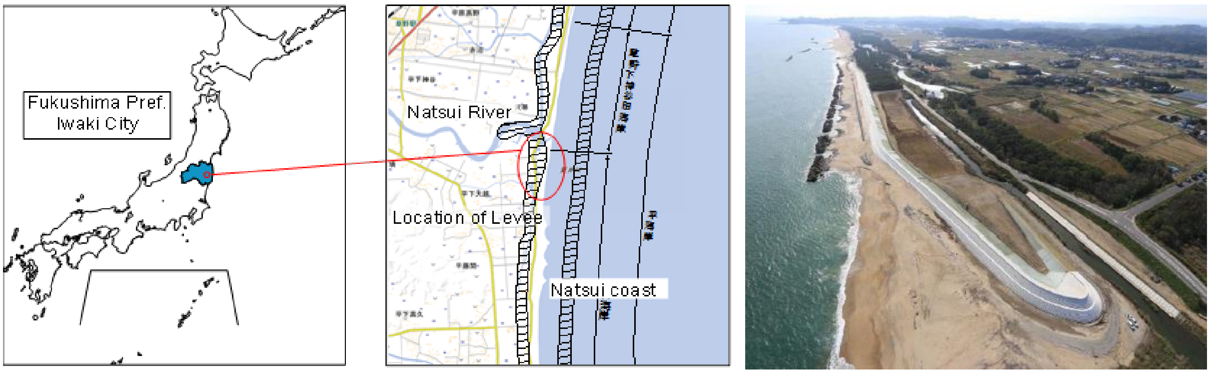


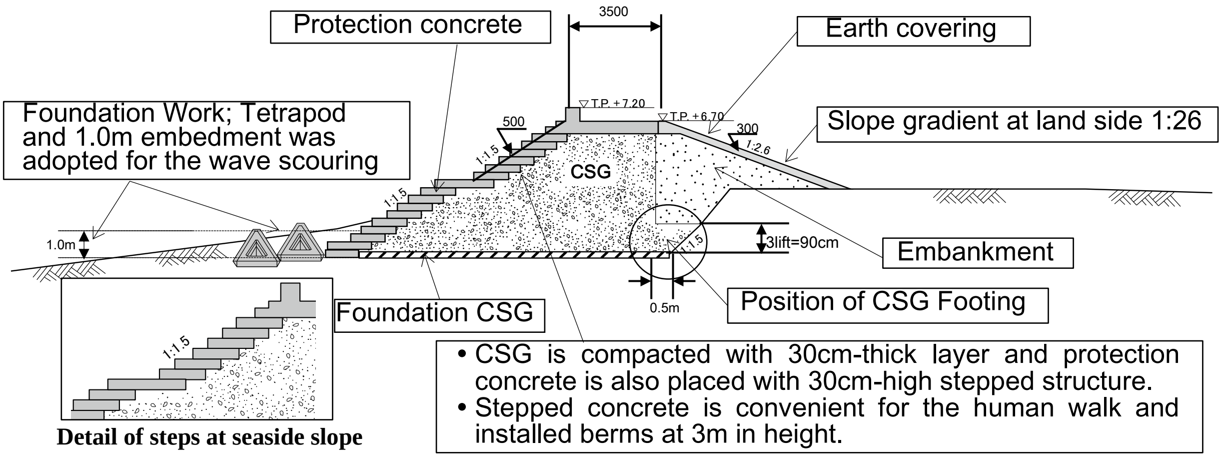
Figure 1. Location and view of coastal levee

Table 1. Specifications of coastal levee

Name	Natsui district coast
Project	Storm surge protection
Owner	Fukushima Prefecture
Length	920 m
Volume	60,000 m^3 (CSG;40,000m^3)
Crest Height	TP＋7.2 m (TP; Tokyo Peil)

2. OUTLINE OF COASTAL LEVEE

As shown in Figure 2, the seaward slope gradient of the CSG body is 1:1.5 and protection concrete was installed on the surface in order to protect it from high wind waves. The banked soil was built at the inland slope in order to preserve the environment and to ensure human accessibility. The reason why the seaward slope gradient was set to 1:1.5 is to apply the technology of trapezoidal CSG dam, so that the reaction force at the bottom face is small and its fluctuation is also minimized. In other words, the gradients used frequently for existing trapezoidal CSG dams are adopted as follows; the seaward slope gradient is 1:0.8, the inland slope gradient is 1:0.8, and total slope gradient is 1:1.6., and the distribution of reaction force at the bottom face is averaged and minimized by using the similar manner as for dams (Japan Dam Engineering Centre 2012). In addition, setting the seaward slope gradient to 1:1.5 ensures the high wind waves countermeasures and easy evacuation from the coast. From the above, the seaward slope gradient was set to 1:1.5 and the basic form of the inland slope was set to a vertical right trapezoid. Additionally, the back of the levee was shaped for easy access to the coast at all time and the introduction of vegetation. The embankment gradient was set to 1:2.6 after considering stability based on the physical properties of soil, and the inland side embankment was used as a transportation way to place CSG while constructing the coastal levee.



- CSG is compacted with 30cm-thick layer and protection concrete is also placed with 30cm-high stepped structure.
- Stepped concrete is convenient for the human walk and installed berms at 3m in height.

Figure 2. Basic structure of coastal levee

2.1 Basic form of CSG body

Using “Japanese Ministry of Construction, Technical Criteria for River Works for Practical Guide for Design (Draft)/Commentary Design Volume (II)” as a reference, 1.0 m of embedment from the earth-surface was ensured in the seaward foundation of the CSG body (Japan River Restoration Network 2008). As for the inland side, a footing about 0.5 m wide was constructed using CSG, considering workability. Transverse joints were installed in the CSG body every 40 m and in the protection concrete every 10 m in a normal direction, respectively. The bitumen materials were used for joint sealers of the protection concrete.

2.2 Surface protection of CSG body

Regarding the protection area of the seaward slope, the high wind wave run-up height of every return period was calculated, and it was determined that the run-up height of about TP+4.3 m was necessary, which is equal to the return period of 50 years. Consequently, the whole surface of the seaward slope was to be protected because of the importance of the structure. Protection concrete was installed step-wise on the seaward slope as shown in Figure 2. It was ensured that protection concrete was 500 mm in thickness, and landings of 1.5 m in width were constructed approximately every 3 m in height. In this way, by setting the seaward slope into a stepped form, access for evacuation from the coast in times of tsunami, etc. is made easier, and the roughness of the seaward slope surface is increased to reduce the run-up height of waves.

2.3 Embankment slope gradient

The gradient of embankment slope was set to 1:2.6, giving a safety factor of more than 1.0, provided that the embankment is stable against seismic movement L1 (k; seismic coefficient = 0.20). The internal friction angle φ of the embankment material was designed as 33 ° (c; cohesion = 0).

Note: Seismic movement L (level) 1; ground motions of the earthquake that occurs rarely
Seismic movement L (level) 2; ground motions of the maximum credible earthquake

2.4 Raw material of CSG body

It was planned to use concrete debris generated around Iwaki City, caused by aftermath of the 2011 Tōhoku earthquake and tsunami, as the raw material of the CSG body. The estimated amount needed for the CSG body was 40,000 m^3. Besides concrete debris, gravel and costal sand were also initially considered as possible raw materials of CSG.

The concrete debris was generated around Iwaki City classified as concrete and bricks. Of the total volume of concrete debris of about 160,000 m^3, up to 130,000 m^3 was available, excluding selected debris. The transport distance from the temporary storage site of the concrete debris to the construction site was about 3.5 km. This concrete debris would be processed as industrial waste if it would not be used as construction material, but we could ensure effective utilization as the raw materials of CSG body. Japan’s Ministry of Environment permits the use of concrete debris in public work projects, and it was legally possible to recycle it for the construction of the Natsui coastal levee.

3. DESIGN OF THE COASTAL LEVEE

3.1 Design procedure

Structural stability investigation of the coastal levee was carried out in the following three points: 1) stability of the CSG body, 2) stability against sliding through the foundation, and 3) subsidence due to soil liquefaction. In the case of not fulfilling three conditions above because of insufficient ground strength, soil improvement was considered and the stability of the foundation was confirmed.

More specifically, structural analysis of the coastal levee was executed by following the procedures below. The flow of structural analysis is shown in Figure 3.

1) Stability of the CSG body (at normal time, at the time of seismic movement L1)
2) Stability against the circular slip through the foundation (at normal time, at the time of seismic movement L1)
3) Subsidence due to liquefaction (at the time of seismic movement L2)

When the required safety was not achieved for the bearing capacity of the foundation, circular slip failure for subsidence after the above investigation, it seemed to come from insufficiency of the ground strength. Therefore, measures for soil improvement (explained in detail at 4.2) were considered and the above procedures from 1) through 3) were analysed again.

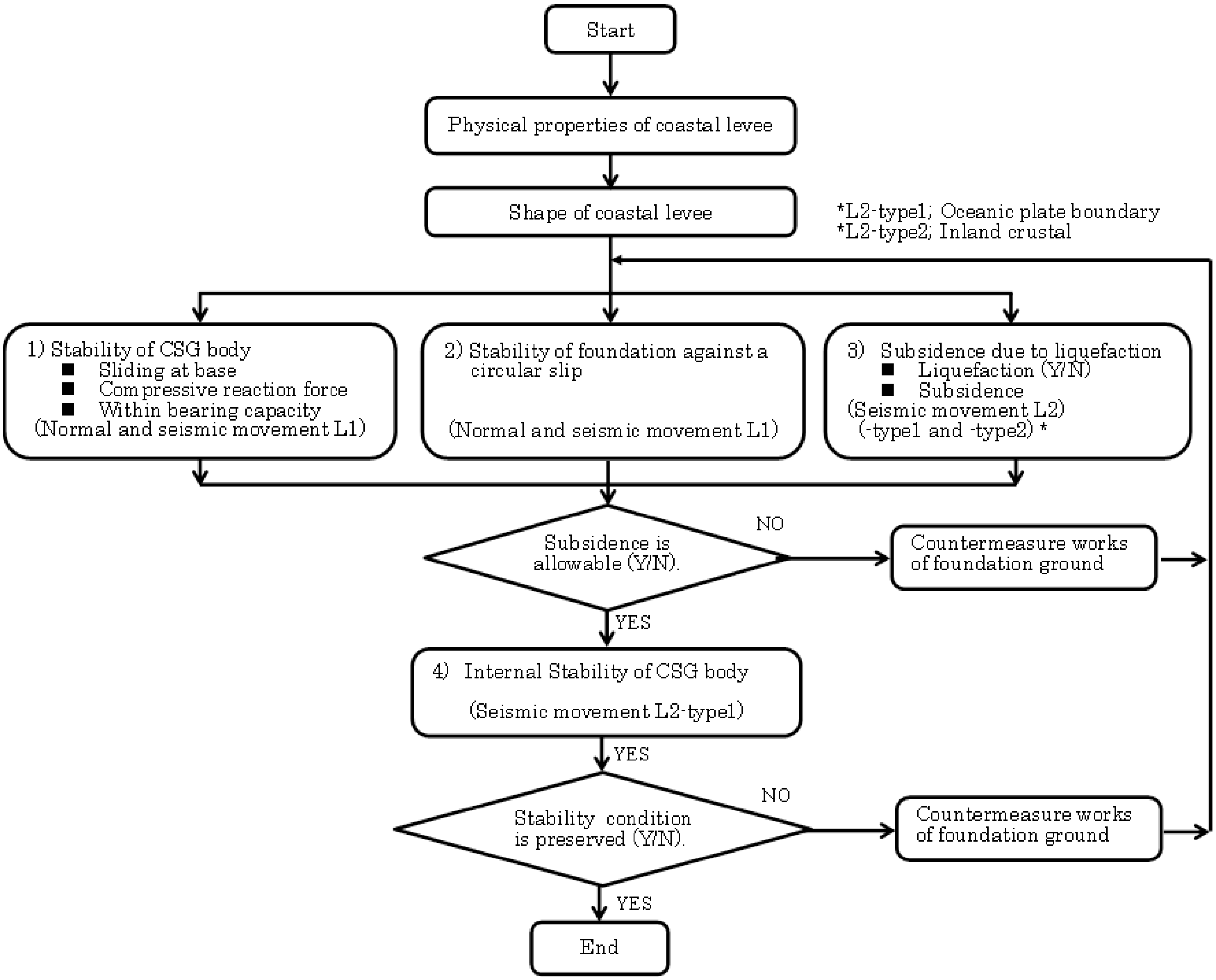


Figure 3. Structure analysis flow

3.2 Stability analysis of CSG body

The stability analysis of the CSG body was carried out to fulfill the following three conditions: i) Stability against the sliding of the base of the body [Fs; safety factor $\geqq 1.5$ (Normal), Fs $\geqq 1.2$ (Earthquake)], ii) Reaction force at the whole base is compressive and iii) Reaction force at the base is within the allowable bearing capacity of the foundation. The loadings to act are hydrostatic pressure, uplift pressure, soil pressure, inertia force, hydrodynamic pressure (from seaside), and own weight as shown in Figure 4. Wave force was not taken into account for the Natsui coastal levee because the slope gradient of seaward surface of the CSG body is 1:1.5. Inertia force was set according to the design seismic coefficient of the seismic coefficient method.

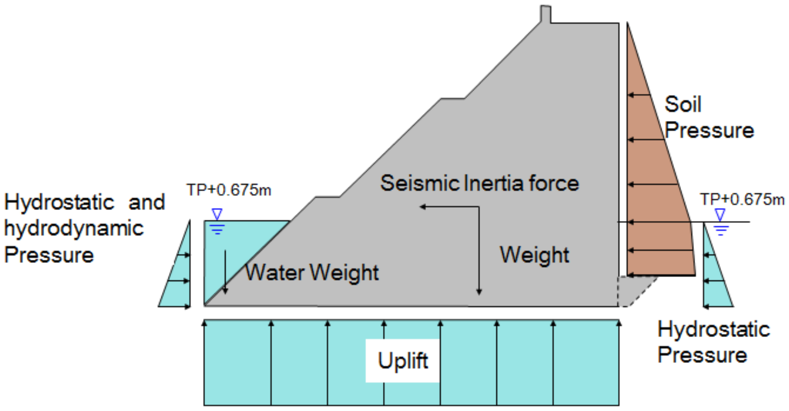


Figure 4. Loading for stability calculation of CSG body
(At the time of seismic movement L1, k; seismic coefficient = 0.2)

Here, cohesion of the foundation ground c, internal friction angle φ, unit weight, and bearing capacity of ground were established to investigate sliding at the base of CSG body. These settings were based on the N-value and the test results using sampled specimens.

3.3 Setting the required CSG strength

The required CSG strength was calculated by elastic analysis of CSG body – foundation model as shown in Figure 5. The loading conditions for analysis corresponded to the loading used for stability analysis for the levee body and the foundation. The required CSG strength was calculated considering the appropriate safety factors for internal stress using 2-dimensional FEM elastic analysis. Here, the required strength was obtained by multiplying the required safety factor by 4 in relation to the calculated internal stress. The required safety factor was set to 4, which is equivalent to a gravity dam with mass concrete.

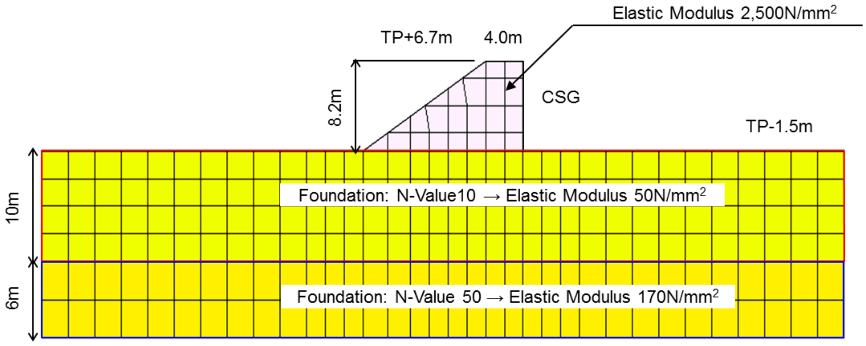


Figure 5. Analysis of required CSG strength of CSG body (by 2-D FEM)

There are two types of unit cement content of the produced CSG: 80 kg/m^3 and 100 kg/m^3. The CSG strengths of each quantity from "Diamond Shape" that was obtained from the peak strength of CSG are 1.7 N/mm^2 and 2.9 N/mm^2 respectively. The particle size distribution of CSG material is shown in Figure 6, and the "Diamond Shape" for 80 kg/m^3 of unit cement content is shown in Figure 7. Here, “Diamond Shape” theory is proposed at the design of CSG dam to determine the required CSG strength (JDEC, 2012).

3.4 Stability of the foundation ground

To support the superstructure safely, the foundation of the coastal levee must be prevented from sliding and subsidence, and should be designed to endure scouring by waves. The foundation ground of Natsui District is a sand layer. The design was carried out by establishing two representative cross-sections with different levee heights based on the N-value from the field boring survey (soil nature, grain size distribution, N-value, etc.). For the investigation of seismicity, the existence of the liquefaction layer was surveyed based on the particle size distribution and the plasticity index of foundation materials in addition to the N-value. The dynamic strength of the foundation was obtained from cyclic tri-axial tests in order to calculate subsidence.

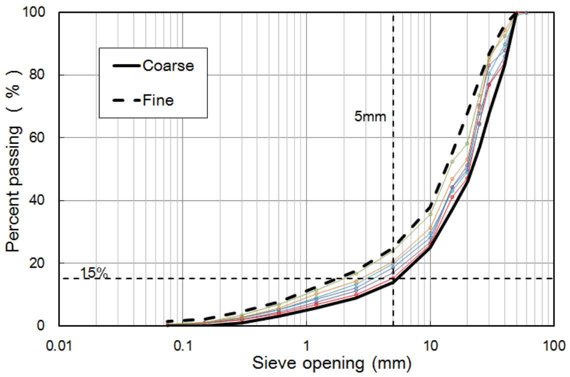


Figure 6. Particle size distribution of CSG material

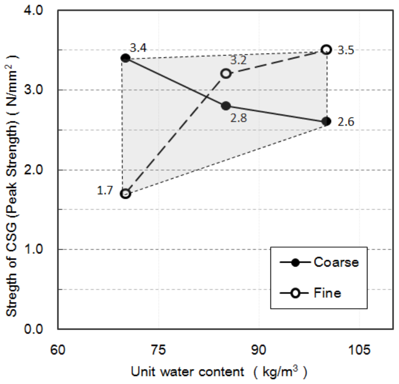


Figure 7. “Diamond Shape” of 80 kg/m^3 of unit cement content

3.4.1 Stability against sliding through the foundation

The stability against sliding surface that passes through the foundation is calculated on the basis of a circular arc analysis at normal times and at the time of seismic movement L1. The loading is set in proportion to the stability analysis of the levee body. The CSG body is not subject to stability analysis because of its strength characteristic, so the stability of the CSG body was confirmed by the circular slip through the foundation. One example of the analysed cross-section is shown in Figure 8. The stability analysis was carried out at normal times with the design high tide level TP+1.42m and at the time of seismic movement L1 (k = 0.20) with the high water level TP+0.675m. The safety factor Fs at the time of seismic movement L1 before the soil stabilization was below 1.0, but after the improvement, the safety factor improved to 1.167 and it exceeded 1.0 of the design safety factor.

3.4.2 Subsidence due to liquefaction

When a liquefaction layer was identified, the investigation of the subsidence at the time of seismic movement L2 was carried out by the liquefaction analysis following the guideline of Water and Disaster Management Bureau (2012). For the stability evaluation, it was confirmed that the height of the coastal levee after subsiding was higher than the receiving water level as shown in Figure 9. A countermeasure against the ground is needed if the height after subsiding is lower than the receiving water level. Figure 9 shows subsidence after the soil improvement.

4. CONSTRUCTION OF COASTAL LEVEE

4.1 Construction of CSG body

In the execution scheme of the CSG coastal levee, the construction cycle was basically considered to ensure effective progress of each work item concerning CSG body, protection concrete, embankment, etc. In this construction, the embankment was also used as the form for CSG placement.

It was necessary to consider a construction cycle where three work items that constitute the coastal levee construction, such as embankment, CSG body and protection concrete, would not stop day after day and each work item would not be operated in the same job site. Therefore, a construction cycle in the following order of embankment, CSG body and protection concrete for the normal direction of the levee was applied to this construction work, as shown in Figure 10. At the same time, three construction sites (Area A, Area B and Area C, which are shown in Figure 10) were prepared for three work items.

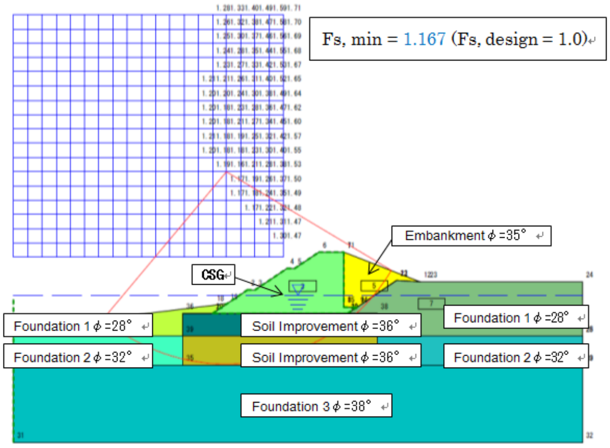


Figure 8. Stability against the circular slip through the foundation

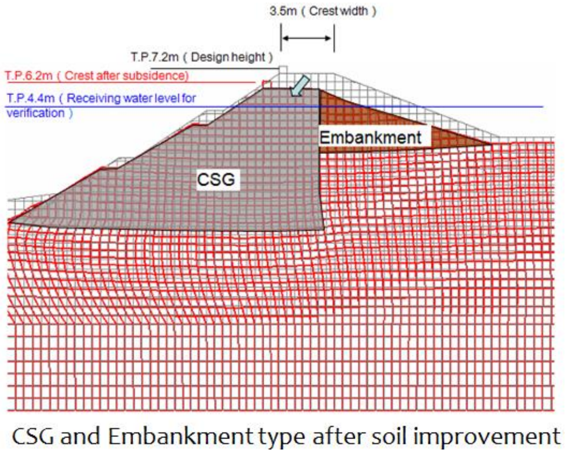


Figure 9. Investigation of subsidence due to liquefaction

4.1.1 Combination of CSG construction machines

The construction quantity of CSG per day was set reasonably, considering the project schedule and the supply capacity of the base material. When choosing the models of the construction machines, we considered the construction quantity per day and the structure of the levee (the width of the levee, structure of the cross section, etc.) as well as the versatility of the machines. In the construction plan of the CSG coastal levee, lift thickness was set reasonably, considering the model of the CSG compacting equipment when forming the embankment.

Construction equipment capable of keeping 50 m^3/hr. of CSG placing speed was chosen for the construction, which has 400 m^3 of average placing quantity per day. As for CSG compacting equipment, 4-ton vibration rollers were chosen and the thickness of one lift was set to 30 cm, which meets the vibratory force of the vibration rollers.

4.1.2 CSG material production facility

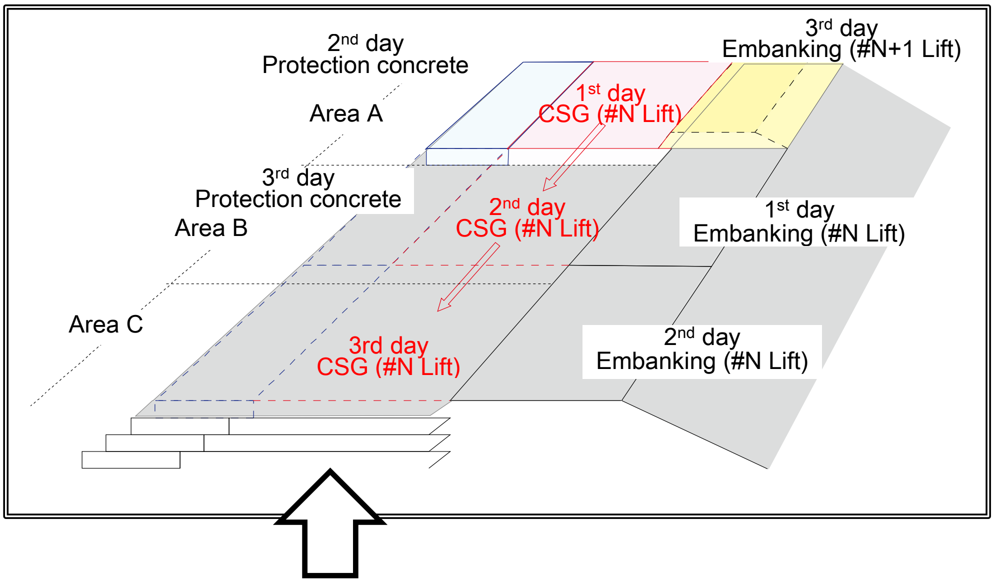
The required production equipment for CSG material was selected in order to make CSG material in the range of grain size distribution determined by the preliminary test construction.

The CSG materials were produced by fracturing concrete debris (see Figure 11), which was the raw material, using a crawler-type crusher (140-kw, jaw crusher) (see Figure 12). The dimension set for the crushing machine was adjusted so that the size of the gravel after crushing would be within the size range of the CSG material. Following the test construction result, the opening size of strand (OSS) was set to be 67mm and closing size of strand (CSS) was 35mm. In addition, there was concrete with metal bars, so before putting debris into the crushing machine, metal bars were removed using the crusher for scantling.

4.1.3 Edge construction

The construction method of the CSG edge was dictated by the construction cycle of both CSG and protection concrete. It is necessary to construct CSG edge that satisfies the required quality and workability of CSG at the boundary with the protection concrete.

For this construction, an end mold using wide-flange beam steel (H-350 mm × 350 mm) was installed in the boundary of CSG and the concrete, and a CSG edge was placed ahead of the protection concrete placement at the construction cycle (see Figure 13). The end mold was not fixed with an anchoring device, and instead we used a heavy structure in which the weight of the steel resisted the lateral pressure when the CSG was compacted.



Area	Lift	1st day	2nd day	3rd day	4th day	5th day	6th day
A	#N	1 MP	2	4			
	#N+1			3 EM	1 MP	2	4
B	#N	3 EM	1 MP	2	4		
	#N+1				3 EM	1 MP	2
C	#N		3 EM	1 MP	2	4	
	#N+1					3 EM	1 MP

EM	End mold for CSG
MP	Mold for Protection concrete
1	CSG Placement
2	Protection concrete placement
3	Embanking
4	Protection concrete curing

Figure 10. Construction cycle of coastal levee

Figure 11. Condition of concrete gravel base material

Figure 12. Manufacturing CSG materials

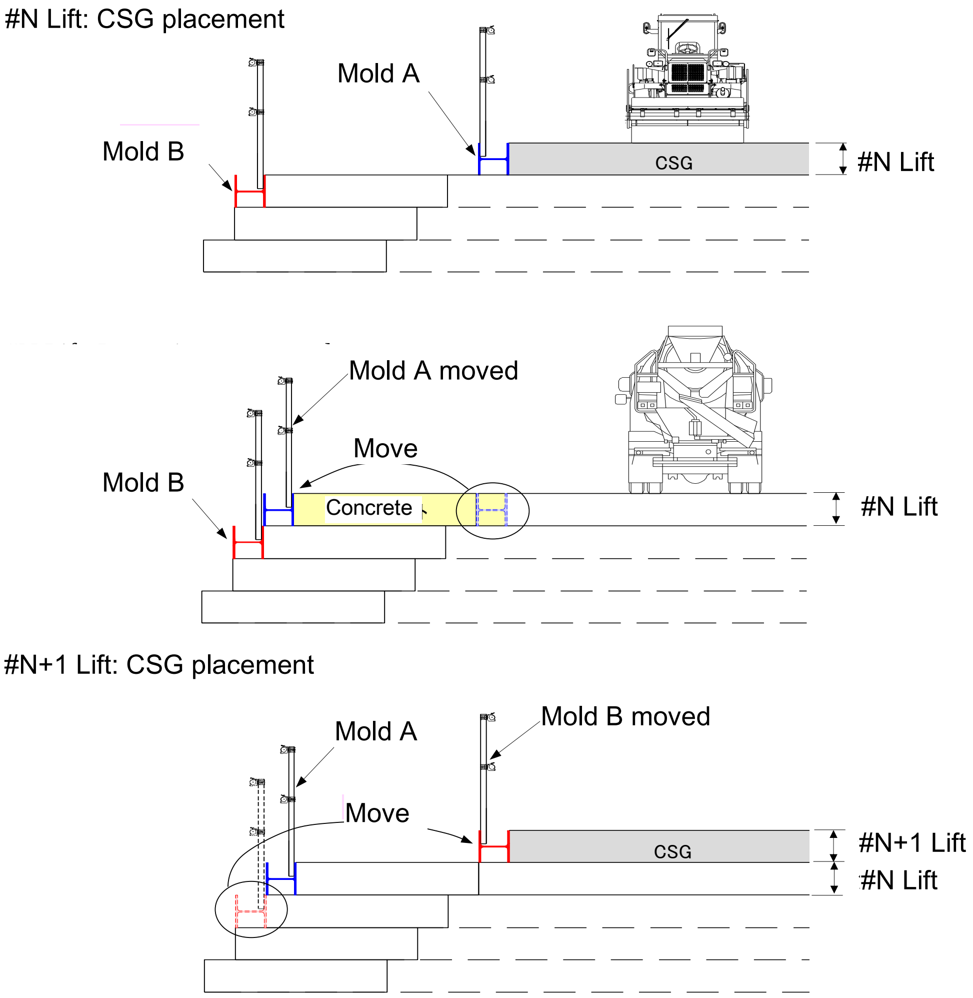


Figure 13. Process of constructing the mold for protection concrete

4.1.4 Protection concrete construction

The outer protection concrete must have durability to protect the CSG body. After placing concrete, curing sheets were covered and spray curing was carried out in order to prevent drying shrinkage of the concrete surface after removing the mold. Bituminous joint material (t = 10 mm) was used at every 10m interval of the protection concrete. The joint material was placed before placing the concrete and was fixed using an end mold (see Figure 14).The end mold for the CSG edge was also used as the mold for the protection concrete as shown in Figure 13. A minimum period of three days were set aside as stripping time for the mold, so two sets of the end mold were prepared with consideration for using them in constructing CSG edge as well. A wooden mold was used for the small diameter curving section of the protection concrete where the construction started.

Figure 14. Construction of protection concrete joint

4.2 Foundation ground construction

4.2.1 Foundation construction

The sand compaction pile (SCP) method, which has been used frequently in the past and is economical for liquefaction countermeasures, was selected for the soil improvement at this area. The construction range of the SCP had to fulfill the requirement for the subsidence caused by seismic movement L2. The range was also lacking the required bearing capacity for the design, so the bearing capacity of ground was improved (see Figure 15).

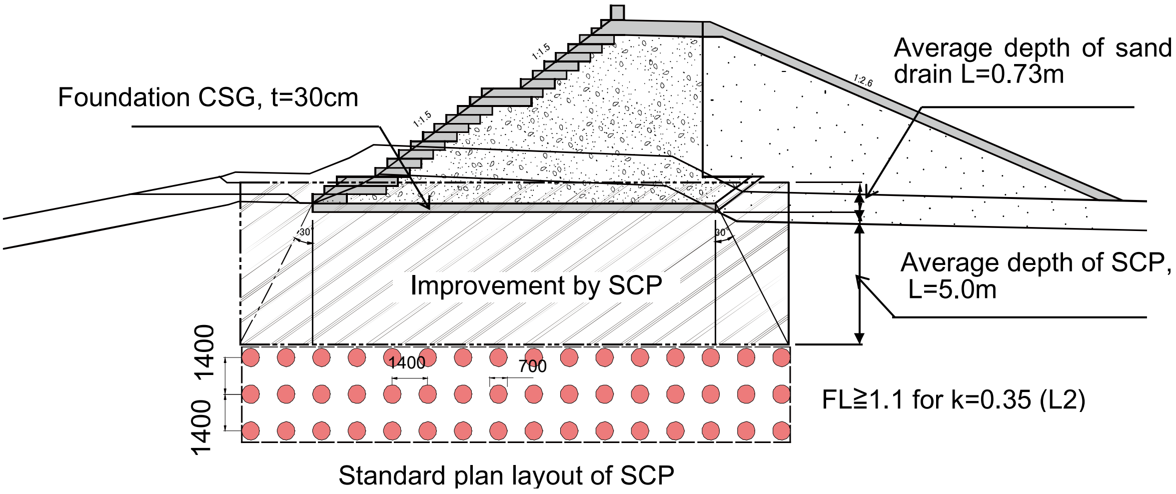


Figure 15. Construction for foundation improvement (1.4 m x 1.4 m grid pattern)
FL；resistance coefficient for liquefaction

4.2.2 Bearing capacity of foundation ground

The improvement range of the foundation was where the required bearing capacity for the CSG body was not assured. Additionally, the location where foundation subsidence was not acceptable because the levee crest subsides below the receiving water level due to liquefaction (L2), and where N-value is less than 17, was also improved. On the other hand, ground improvement was not carried out at the place where the levee crest did not subside below the receiving water level due to liquefaction at the time of seismic movement L2, and where the height of the CSG body was rather low and the higher bearing capacity was not required but N-value of ground showed 12 or higher (see Figure 16).

The settlement rate at the placement of the casing pipe during SCP work was used to confirm the required depth of the ground improvement, and the relationship between the N-value and the settlement rate was prepared in advance.

4.2.3 Foundation CSG construction

By placing the foundation CSG on the base ground surface of the coastal levee, the elastic modulus of the base ground surface was improved so that the compaction energy of the vibrating roller was positively transmitted to CSG. In addition, a rich mix of CSG with 100 kg/m^3 of unit cement content was used for the foundation CSG (see Figure 2).

The crawler dump truck that transported CSG was driven on the leveled CSG material to prevent damage to the base ground surface and contaminating CSG with sand. Furthermore, transported CSG was leveled in the direction of the placing site and the bulldozer could spread CSG without disturbing of the base ground surface.

Figure 16. Construction of sand compaction pile

5. CONCLUSION

By adopting trapezoidal CSG dam technology, not only does it have a “permanent” structure toward overflows of sea wave, but both material cost and disposal cost were reduced by using concrete debris from the aftermath of the earthquake. In addition, we were able to greatly shorten the construction period: Construction of the Natsui CSG coastal levee was finished in about 11 months and it took about seven months to complete the CSG body of the coastal levee.

6. REFERENCE

Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2011). *The method of setting the water level of design tsunami -Criteria for determining the height of coastal levees as the basis of the reconstruction plan-.* (in Japanese).

Iwaki Construction Office, Fukushima Prefecture (2013). *Natsui District Coast, CSG Coastal Levee Technical Information.* (in Japanese).

Japan Dam Engineering Centre (2012). *Engineering Manual for Design, Construction, and Quality Control of Trapezoidal CSG Dam*. Japan Dam Engineering Centre.

Japan River Restoration Network (2008). *Japanese Ministry of Construction, Technical Standards for River Works :Practical Guidelines for Design.* Sankai-doh Press. (in Japanese).

Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2012). *Guideline and commentary of seismic performance analysis of river structures.* (in Japanese)