DESIGN AND CONSTRUCTION GUIDELINE OF INTEGRAL ABUTMENT BRIDGES FOR JAPANESE HIGHWAYS

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Abstract

This paper introduces the design and construction guideline used for integral abutment bridges in Japan's highway systems. This guideline was formulated based on inspections and investigations of existing integral abutment bridges, studies on maintenance problems and seismic design issues, etc. .

Introduction

To reduce the total investment cost of road bridges, it is important to reduce the maintenance costs in addition to the initial costs. One reason contributing to high maintenance costs is damage to bearings at the abutment and the expansion joints. Particularly, the ratio of costs for bearings and expansion joints relative to the total cost of the road bridges is high for short and medium class bridges. To resolve these problems, it is effective to introduce the integral abutment structures which can omit bearings and expansion joints. Figure 1 shows a comparison of the structural characteristics between the integral abutment bridge and the conventional bridge.

Integral abutment bridges are not widespread in Japan although this type of bridge was first introduced experimentally about 20 years ago. The reason is the serious maintenance challenges such as the cracks in the pavement between the abutment and the approach embankment, and the lack of adoption of systematic design methods. Moreover, seismic design of the structure is also a key factor in Japan, just as it is in some U.S. states. However, it was not clear in earlier periods whether the seismic performance verification methods for integral abutment bridges were appropriately executed, especially for extreme earthquake events such as Level 2 earthquakes.

Against this background, in 2006, PWRI commenced research of design and construction methods for integral abutment bridges as a cooperative program involving four technical associations. This work led to the issue of the new guideline in 2012. The

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table of contents of the guideline is shown in Table 1. This paper introduces some key points of the guideline as applied to Japanese road bridges.

Basic Structure and Scope of Application

Figure 2 shows the basic structure of an integral abutment structure. The basic structure consists of two parts; 1) main structure of the integral abutment bridge to include an integrated superstructure, abutment wall and foundation, and 2) the approach embankment contiguous to the main structure.

With respect to bridge length and number of spans, this guideline applies to a single span bridge with a length of less than about 40 m. This is because the designs for constraint of allowable lateral displacement at the top of the abutment (described here later) as well as for constraint of reaction force of the superstructure which uses abutment support with single row pile foundations. In order to determine the scope of application of length, a parametric analytical study was used to verify the allowable lateral bearing capacity of pile foundations. This result showed that the verification parameter was satisfied for a case where maximum span length was 40 m with steel girder bridges, or 30 m with PC girder bridges.

The limitation height of the abutment is approximately 10 m since lateral displacements at the top of the abutment and the top of the pile become greater as the abutment height rises due to the influence of earth pressure.

Normally, the shape of the superstructure is a straight bridge . This is because structural behaviors for skewed bridges are uncertain when the action direction of inertial force of superstructure differs from that of the passive earth pressure from backfill. Moreover, there has been considerable experience of damage such as cracking of the abutment walls or at the end of girder due to torsional deformation of the superstructure, or peeling of cover concrete of the abutment wall. From a similar point of view, integral abutment bridges should not be applied when the backfill earth pressure might not apply to the abutments in good balance. These situations correspond to conditions where the height of abutments on either side or the height of an abutment in the transverse direction is remarkably different.

The material of approach embankment (backfill) should be generally sand or sandy gravel soil which compacts well; artificially lightweight materials are not recommended.

Considering deformation capacity of the foundation, the pile length between the bottom of the abutment wall and the top of the supporting layer shall be kept greater than 4 m. This concept and length is corresponds to parameters of the Oregon State bridge design manual (v2008).

It is fundamentally not recommended to position integral abutment bridges on ground subject to risks of lateral movement of ground, subsidence over extended periods, liquefaction, or where liquefiable induced lateral flows are likely to occur. If an integral abutment bridge is constructed on such ground conditions, it should be designed carefully to give full consideration to changes in ground condition. This is the same factors which mean we cannot expect much from the passive ground resistance of backfill subject to subsidence. It is effective to harden the foundation backfill ground as a countermeasure to lateral ground movements. However, it is not recommended to utilize this method because it also restrains deformation of pile foundations.

Loads and Load Combinations

Applying load of the structural members of the integral abutment bridge should be varied depending on the construction steps such as the timing of integrated superstructure to substructure. Moreover, it is important to consider the statistically indeterminate forces of thermal effect, creep, shrinkage, prestressed force, et al.

In case of load combinations including earth pressure, designs should consider the section forces, assuming severest case scenarios due to the following two parameters; one is application of the total earth pressure to structure, the other is half that pressure. However, the load combination which applies half of the total of earth pressure with seismic force can be omitted.

In considering the load combination including lateral pressure due to overburden load, it should be considered that lateral pressure is applied to the structure for three scenarios; one side, both sides and not at all. Additionally, the cases of a half of total lateral pressure should also be considered.

Table 2 shows the list of loads and load combinations in the design of the integral abutment bridge.

Fundamental Principal of Verification

1) Performance Requirements and Limit States of Bridge

The performance requirement of the bridge is to ensure the ordinary functions of bridges with the moderate maintenance under both ordinary and storm conditions, and with only simple repairs under Level 1 earthquake condition.

It can be omitted verifications under Level 2 earthquake condition of the integral abutment bridges which are designed to be verified under ordinary condition and Level 1 earthquake condition in case of satisfied the scope of application in this guideline. This situation is as same as for conventional abutments. However, the structural characteristics of integral abutment structures are different from those of conventional abutments because the substructure is directly integrated into the superstructure.

Therefore, dynamic time historical analyses using finite element models were conducted for two cases in order to evaluate the response behavior of integral abutment bridge under Level 2 earthquake conditions. One was for a bridge with backfill soil, the other had none. Modeled bridges were designed to satisfy the verifications under both ordinary conditions and Level 1 earthquake conditions. The results showed that response acceleration at the top of the abutment wall did not amplify it from the bottom of the wall.

It was found that response behavior of the abutment dominated that of the backfill, just as occurs in conventional bridges.

The analytical maximum section force using finite element models for a Level 2 earthquake was approximately equal with using 2-D frame models under ordinary condition and Level 1 earthquake condition. This trend was also found in the lateral response displacements at the head of pile and at the top of the abutment wall.

In addition to these findings, it was also confirmed as follows.

a) Rigid frame bridges with structural characteristics similar to integral abutment bridges have never been serious damaged by in extreme earthquakes of the past, including the Great East Japan Earthquake in 2011, even where verification under Level 2 was omitted.
b) It was also confirmed that the integral abutment bridges were damaged slightly in comparison with conventional ones in the 1994 Northridge earthquake.

Table 3 shows the limit states of each structural member based on performance requirements of integral abutment bridges.

2) Verification Method, Items and Values for Verification

Seismic performance of integral abutment bridges of lengths up to 100 m should generally be verified using the static analytical method, because it is confirmed that these structures are dominated by the primary mode as a result of the influence of backfill.

Verification items and values are shown in Table 4. The characteristic point is the allowable lateral displacement at the top of the abutment wall (15mm). This verification value is determined with respect to the damage of the pavement which often develops in the road surface between the abutment and the approach embankment, due to girder expansion and contraction from thermal effects. It also takes into account, design examples in U.S. that allow displacement of 1 inch (approx. 25mm) and research results from Hirakawa et al (2006) finding that passive earth pressure of the approach embankment tends to increase as the abutment wall deformed repeatedly from expansion and contraction of the girder.

Structural Analysis

Structural analysis should be used as the model to simulate statistically indeterminate structures. It can be modeled as 2-D frame model in case where the bridge is straight. It should be analyzed duly considering the construction processes.

For verifications of expected performance under ordinary conditions, response force and deformation are basically evaluated based on elastic theory, because it is required that each structural member and ground resistance of the integral abutment bridges remain within the elastic ranges. In general, this analytical model is also fundamentally used for verifications of likely performance under Level 1 earthquake and storm conditions because the limit states are the same.

The Passive ground resistance of the backfill soil is modeled as an elastic spring because the limit state of backfill soil should be set to remain within the elastic ranges. Although it is better to set the design geotechnical parameters based on in-situ test for constructed backfill soil, the parameters shown in Table 5 can be set in the design stage on the supposition that backfill is constructed appropriately as per the construction methods set in this guideline.

Design of Structural Members

The superstructure / substructure connection should be rigidly designed. These parts should be designed to transmit section force smoothly and with good duration in consideration of construction process, change of structural system.

For example, tension stress of concrete at connection should remain, and preclude cracking or similarly induced bad effects in view of strength and duration of the bridge. It is also effective to use coated reinforcement bars for better corrosion protection.

At the substructures of the integral abutment bridges constructed in Japan, there have been seen defects such as separation of free line caused by penetration of the water into the construction joint and separation of rust fluids. To cope with these water related problems, a drainage layer should be installed in the approach embankment along with countermeasures such as paint coating at the construction joint of the backside of the abutment wall. For prevention of penetration of the road surface drainage into the backside of abutment, a partial cross section at the top of the abutment wall is raised up to level of road surface (Figure 3).

The abutment wall / pile connections should be designed to transmit section forces are induced by the superstructure and earth press smoothly from the wall which to the foundation. In the case of the integral abutments, the piles are directly connected to abutment wall so to better set the effective widths, designed in consideration of stress distribution. Effective width shall be set for bending moment design. Effective width, with respect to shear force, is equal to the entire width in consideration of the damage mechanism of wall and design of footing.

Section Force of the abutment wall should be verified at not only the critical section force but also the bottom of the abutment wall. The reason is that section force at the bottom of the abutment wall might become severe condition in a design due to the influence of effective width. Verification sections and effective width of the abutment wall are shown in Figure 4. An abutment wall installed as shown in Figure 5 has sufficient strength capacity similar to piles connected to the footing.

The verification of strength capacity at the top of the pile was conducted with the requisite condition to bury the pile in the wall to 100mm. Figure 5 shows the example of the reinforcement bar arrangement at the head of pile.

These are determined based on the verification results by 3-D finite element model analyses. The height of abutment wall / pile connection is determined based on the analytical results by using the 3-D finite element model. For example, figure 6 shows the stress distribution of the vertical reinforcement bars that are installed in the abutment wall. It was found that the stress became large within the range of twice the diameter of the pile from the bottom of the abutment wall.

Design and Construction of Approach Embankment

The Highway Bridge specifications newly issued in 2012 also include new regulations regarding the approach embankment. The approach embankment should be designed and constructed to keep the continuity of the road surface between the bridge and the embankment adjacent to the abutment. The approach embankment should be constructed using soil material that compacts well and ensures sufficient stability and drainage. Since the backfill is expected to provide resistance, the specifications of the approach embankment of the integral abutment bridge are higher than the other type of abutments in the area and the control standard values for soil compaction.

These specifications of material and construction control standard value are determined with reference to those of roadbed and foundation embankment of small abutments constructed on it. An example of the control standard value of soil compaction is shown in Table 6 and arrangement of drainage layer is shown in Figure 7.

There have been recent cases where mechanically stabilized soils or lightweight material such as EPS has been used for backfill. These cases are not subject to the new guideline because it is not clear what to expect from the constant geotechnical reaction of backfill and it is generally difficult to repair when it is damaged by residual deformation.

Concluding Remarks

The specification for integral abutment bridges was newly introduced as one of the jointless structures at abutment in the specifications for highway bridges Part IV Substructures, revised in February 2012. We expect to broaden the use of integral abutment bridges in Japan by introducing specifications and the use of this guideline.

We continue to investigate and research the structural details of superstructure / substructure connection and time variation with time of earth pressure of backfill to upgrade the guideline.

References

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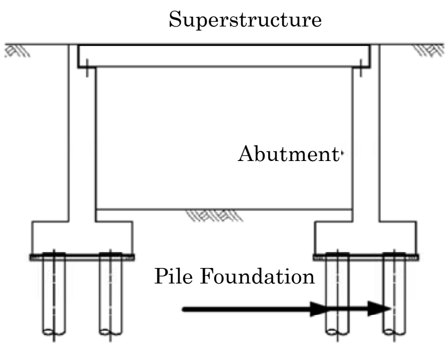
Oregon Department of Transportation: Bridge Design and Drafting Manual 2004, 2008

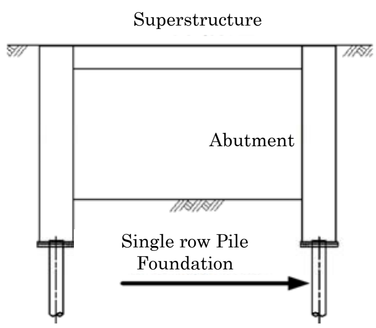
Public Works Research Institute, Japanese Technical Association for Steel Pipe Piles and Sheet Piles, Japan Prestressed Concrete Contractors Association and Japan Civil engineering Consultants Association: Cooperative research reports of design method of Jointless structure of abutment (Part3), Cooperative research reports of PWRI No.404. 2012

Figure 1 Comparison of bridge structural characteristics

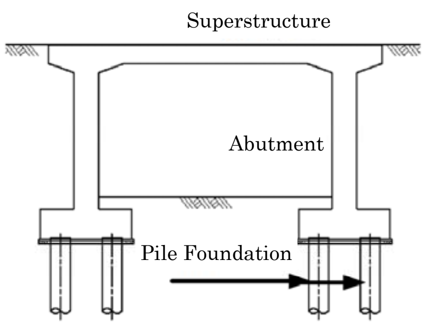
Structural type	a) Conventional bridge	Jointless Structure	
		b) Integral abutment	c) Portal frame
Bearing support	Install	Uninstalled (rigid frame)	Uninstalled (rigid frame)
Expansion joint	Install	Uninstalled (omit)	Uninstalled (omit)
Girder adjustment of expansion from thermal changes	Deform by the foundation	Deform by the flexible pile foundation	Resist by the rigidity of backwall and foundation



a) Conventional bridge



b) Integral abutment bridge



c)Portal Frame bridge

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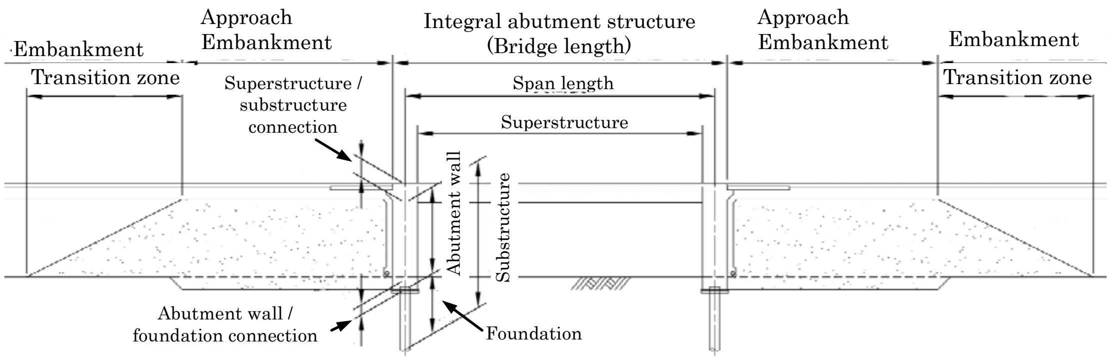


Figure 2 Basic structure of the integral abutment bridge

Table 2 List of loads and load combinations

	Case of Load Combination	Notation
1	Dead Load	(P)*＋E
2	Ordinary condition	(P)*＋L＋i＋E
3	Ordinary condition（Lateral pressure →） **	(P)*＋L＋i＋E＋E_{LL}
4	Ordinary condition（Lateral pressure←） **	(P)*＋L＋i＋E＋E_{LR}
5	Ordinary condition（Lateral pressure for both side）	(P)*＋L＋i＋E＋E_{LL}＋E_{LR}
6	Ordinary condition（Earth Pressure 1/2）	(P)*＋L＋i＋1/2×E
7	Ordinary condition（Lateral pressure→， Earth Pressure 1/2） **	(P)*＋L＋i＋1/2×（E＋E_{LL}）
8	Ordinary condition（Lateral pressure←， Earth Pressure 1/2） **	(P)*＋L＋i＋1/2×（E＋E_{LR}）
9	Ordinary condition（Lateral pressure for both side, Earth Pressure 1/2）	(P)*＋L＋i＋1/2×（E＋E_{LL}＋E_{LR}）
10	Temperature condition	(P)*＋L＋i＋E＋T
11	Temperature condition（Lateral pressure→） **	(P)*＋L＋i＋E＋E_{LL}＋T
12	Temperature condition（Lateral pressure←） **	(P)*＋L＋i＋E＋E_{LR}＋T
13	Temperature condition（Lateral pressure for both side）	(P)*＋L＋i＋E＋E_{LL}＋E_{LR}＋T
14	Temperature condition（Earth Pressure 1/2）	(P)*＋L＋i＋1/2×E＋T
15	Temperature condition（Lateral pressure→， Earth Pressure 1/2） **	(P)*＋L＋i＋1/2×（E＋E_{LL}） ＋T
16	Temperature condition（Lateral pressure←， Earth Pressure 1/2） **	(P)*＋L＋i＋1/2×（E＋E_{LR}） ＋T
17	Temperature condition（Lateral pressure for both side， Earth Pressure 1/2）	(P)*＋L＋i＋1/2×（E＋E_{LL}＋E_{LR}） ＋T
18	L1 earthquake condition (inertia force→)**	(P)*＋EQ→＋E_{EQL}
19	L1 earthquake condition (inertia force←)**	(P)*＋EQ←＋E_{EQR}

*(P) : Principal loads except for Live load, Impact, Earth pressure, Water Pressure, Uplift or Buoyancy.
In general, it means Live load, Prestress, Creep and Shrinkage

**Arrow mark means loading direction.

*** The relationship between the sort of loads and notation is as follow:

Load	Notation
Live load (including impact)	L＋i
Ordinary Earth Pressure (Static Earth Pressure)	E
Lateral pressure due to overburden load	E_{LL}， E_{LR}
The effect of temperature change	T
Inertia force under earthquake condition	EQ
Active earth pressure under earthquake condition	E_{EQL}， E_{EQR}

Table 3 Performance requirement and limit states of each structural member
(Under Ordinary, Storm and L1 earthquake conditions)

Performance requirement of bridge		To ensure the normal functions of bridge (no damage)
Limit state of bridge		・States that the mechanical properties could be kept within the elastic range ・States that the deformation or displacement in the view of serviceability and safety of bridge are not occurred.
Limit states of structural members of integral abutment bridges	Superstructure, Superstructure/substructure connection, Abutment wall, Abutment wall/foundation connection	・States that the mechanical properties could be kept within the elastic ranges ・States that bridge serviceability can be maintained despite deformation
	Pile foundation	・States that the mechanical properties could be kept within the elastic ranges ・States that the deformation could be kept reversibility
	Approach Embankment	・States that the deformation could be kept with moderate maintenance

Table 4 Verification items and verification values

Structural member or part	Main Verification items and verification values	
	Stability Verification	Design of Structural members
Superstructure	—	・Working stress <Allowable stress ・deflection due to live load <Allowable deflection etc*
Superstructure/ substructure connection	—	・Working stress <Allowable stress
Abutment wall	・Response lateral displacement at the top of the abutment wall <allowable lateral displacement(15mm)	・Working stress <Allowable stress
Abutment wall / foundation connection	—	・Working stress <Allowable stress
Pile foundation	・Reaction Force <Allowable Bearing Capacity ・Response displacement <Allowable lateral displacement	・Working stress <Allowable stress
Approach Embankment	・Performance of approach embankment is endured to be designed by chap. 4 in Part 2.	—

*This is specified in specifications for highway bridges Part II (Steel Bridge) or Part III (Concrete Bridge), 2012

Table 5 Geotechnical parameters of the approach embankment

Unit Weight	Modulus of Deformation	Angle of Shearing Resistance
$18 kN/m^3$	$10 MN/m^2$	40deg.

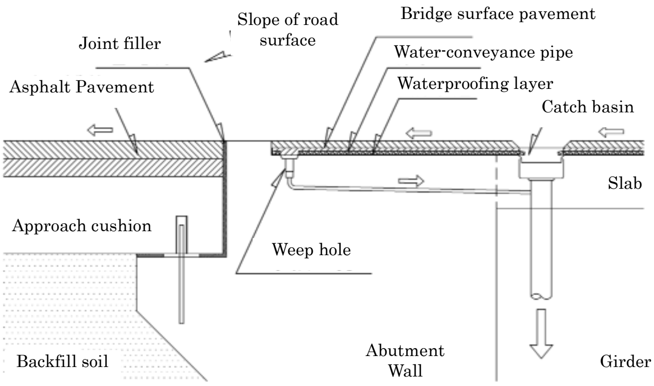
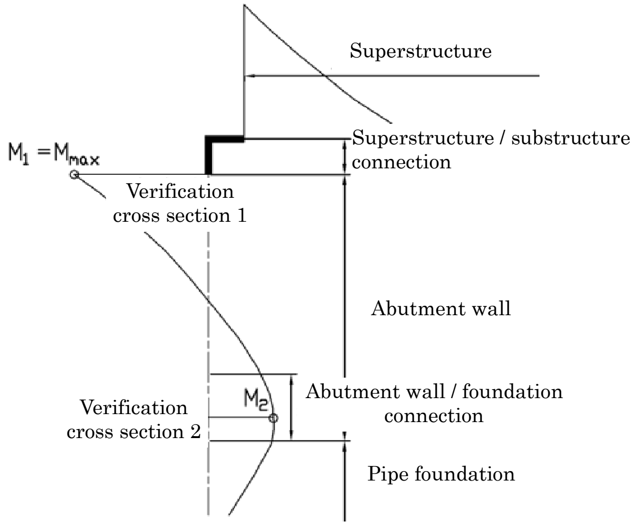
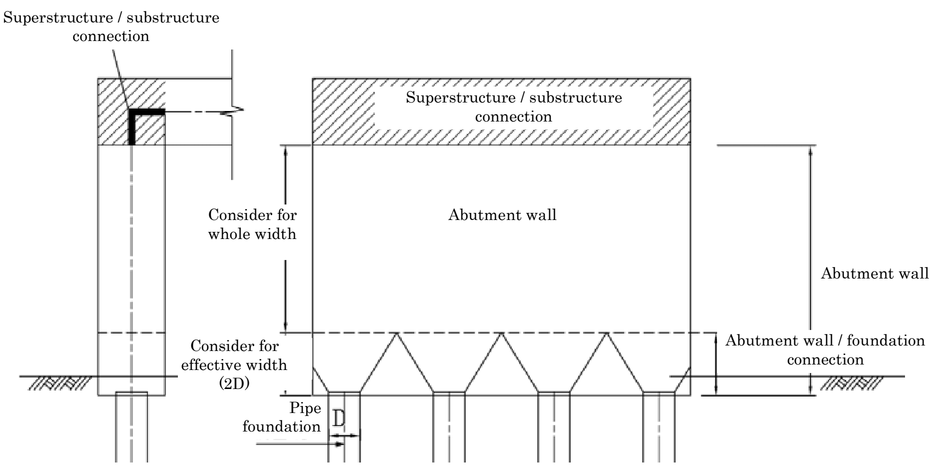


Figure 3 Improvement of the shape of abutment wall



(a) Verification section



(b) Effective width

Figure 4 Verification section and effective width of abutment wall

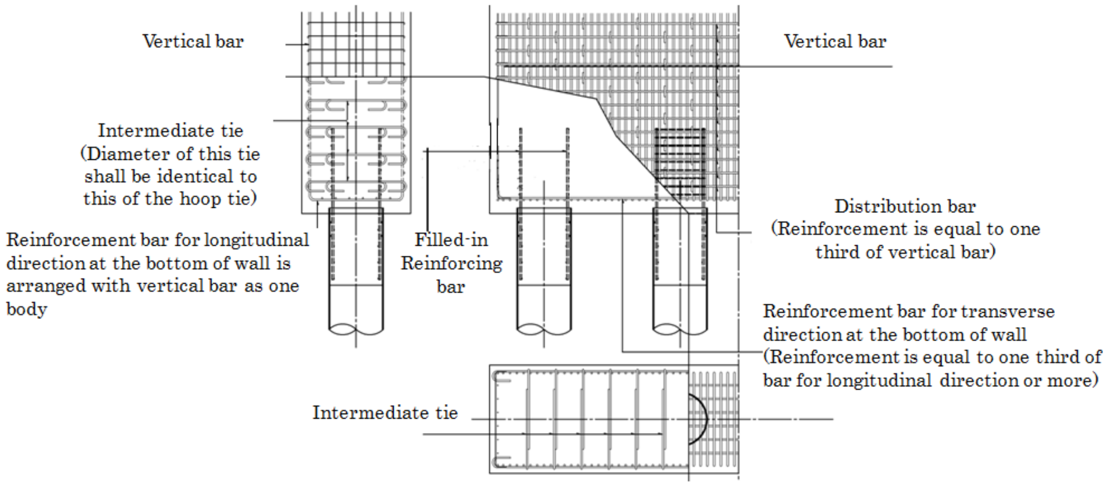


Figure 5 Reinforcement bar arrangement of the abutment wall

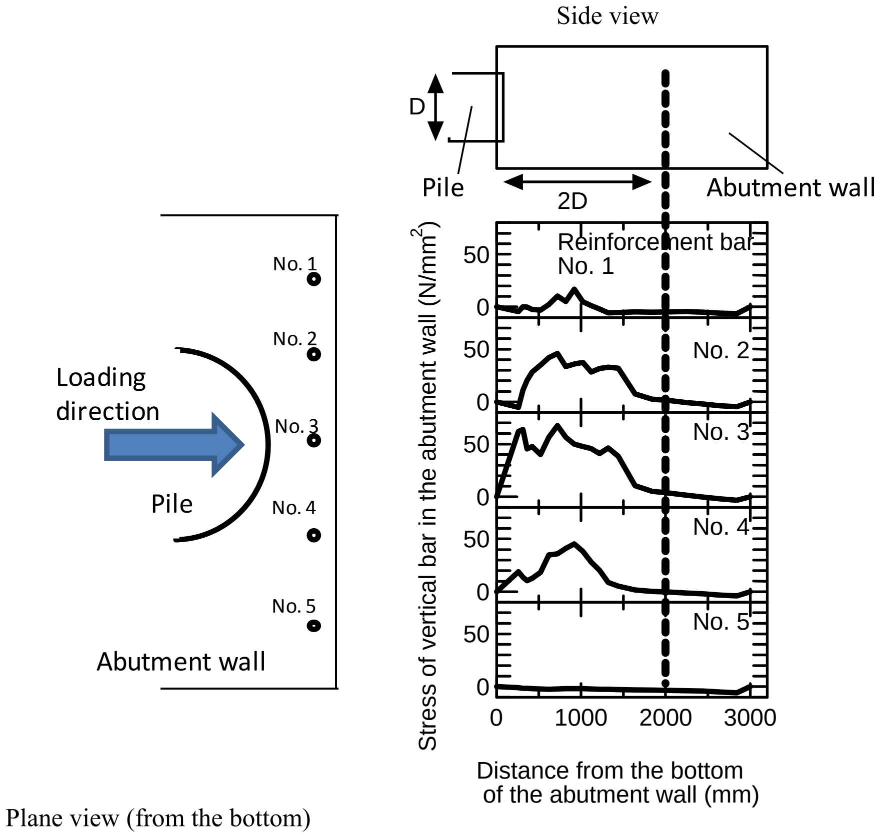


Figure 6 Stress distribution of the vertical reinforcement bars in the abutment wall

Table 6 Example of control standard value of soil compaction
for the approach embankment

Control standard value of soil compaction*	$D_c >$ Average 97%, Minimum 95%
Finish thickness	Less than 200mm

*1 : Applying in the case of sandy soil. Degrees of compactions are verified average and minimum values of them which measured each control construction height.

*2 : These control standard value is used in case of the C ,D or E type compaction methods.

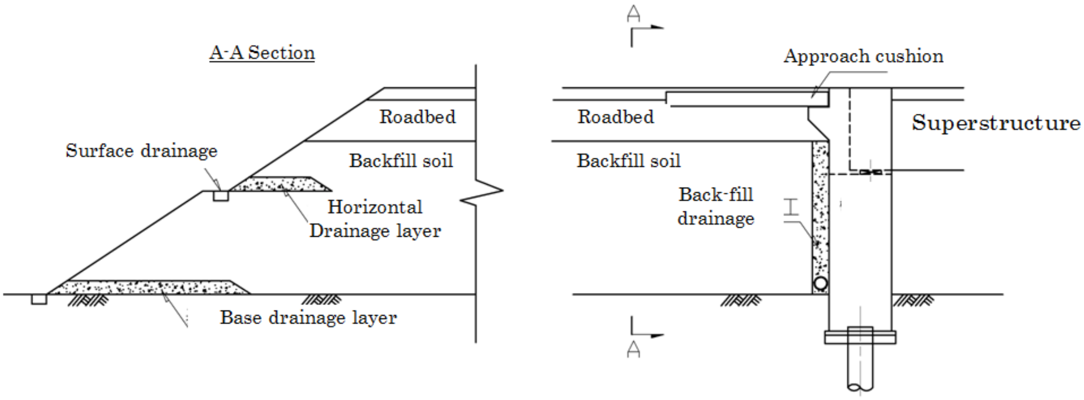


Figure 7 Example of arrangement of the drainage layer