APPLICATION OF WIB FOR BETTER SEISMIC PERFORMANCE OF BRIDGE FOUNDATION

Hirokazu TAKEMIYA[1], Feng CHEN[2], Jorge SHIMABUKU[3]

[1] Professor, Department of Environmental and Civil Engineering, University of Okayama
Tsushima-Naka, 3-1-1, Okayama 700, Japan, e_quakes@cc.okayama-u.ac.jp
[2] Ph.D. Candidate, Department of Environmental and Civil Engineering, University of Okayama
Tsushima-Naka, 3-1-1, Okayama 700, Japan, dns14616@cc.okayama-u.ac.jp
[3] Ph.D., Seismic and Environmental Engineering Department, Kozo Keikaku Engineering
Chuo 4-5-3, Nakano-ku, Tokyo 164, Japan, shimabuku@kke.co.jp

The honeycomb-shaped WIB (Wave Impedance Barrier) measure is proposed herein to be a promising countermeasure for seismic design. A SSPI (Seismic Soil Pile Interaction) system is investigated here for the effectiveness of the WIB method. The computation is conducted by the time domain FEM-BEM hybrid technique. Through the parametric study, the authors pursued optimizing the WIB measure design for better seismic performance of the total system. The results show that the proposed procedure can reduce seismic response remarkably.

***Key words**: Honeycomb-shaped WIB, SSPI, time domain, FEM-BEM, seismic mitigation*

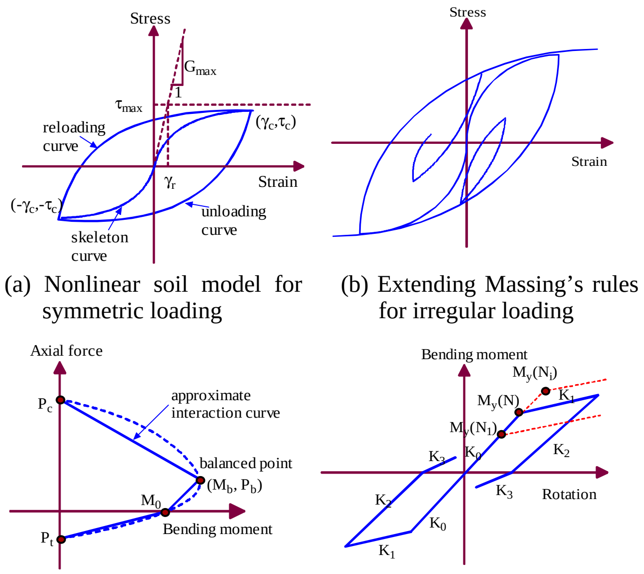
1. INTRODUCTION

Pile foundations are widely used to support civil engineering structures especially at soft sites. Important structures, such as bridges, are demanded of sufficient seismic resistance at foundations. Conventionally, improving horizontal impedance of pile foundations is carried out. At the same time, improving soil partially where the piles are embedded is also an effective measure[1)]. In this paper, WIB (Wave Impedance Barrier) which was firstly developed in the Takemiya lab to mitigate traffic induced vibration, is proposed to improve seismic resistance. The basics idea of WIB is on the control of wavelengths in the concerned wave field. The construction is made of soil-cement columns. Herein, an extension study is conducted for application of the WIB to seismic problem.

2. METHODOLOGY OF ANALYSIS

The analysis is based on the two dimensional time domain FEM-BEM (Finite Element Method and Boundary Element Method) hybrid technique. This hybrid method utilizes the advantages of respective discretization methods. The FEM covers the structure and the near field soil with complicated zone of the model flexibly, while the BEM fulfills the infinite boundary condition inherently. Therefore, the deeper extending stiff soil layer belongs to the BEM domain. The pier and piles are modeled by beam elements, and the neighboring soil is discretized by isoparametric solid elements. At the edge of the FEM zone, artificial high damping is imposed for absorbing the outgoing waves.

The nonlinear behavior of soil elements is characterized by the Mohr stress circle criterion and the hysteretic hyperbolic model proposed by Hardin and Drnevich[2)]. The inelastic behavior of RC beam elements are described by the one component model proposed by Giberson[3)] with considering both sway and rotational motion at both ends of each element. The hysteretic characteristic of the RC beams is represented by the modified Q-Hyst model[4)] by taking into account of the relationship between bending moment and axial loading. **Figure 1** describes the above mentioned nonlinear performance for solid elements and beam elements. At every computational step, the yielding bending moment is revaluated by the axial load from the bending moment-axial force interaction diagram.



(a) Nonlinear soil model for symmetric loading

(b) Extending Massing's rules for irregular loading

(c) Yielding Bending moment considering axial load

(d) Modified Q-Hyst model

Figure 1. Nonlinear mathematic models

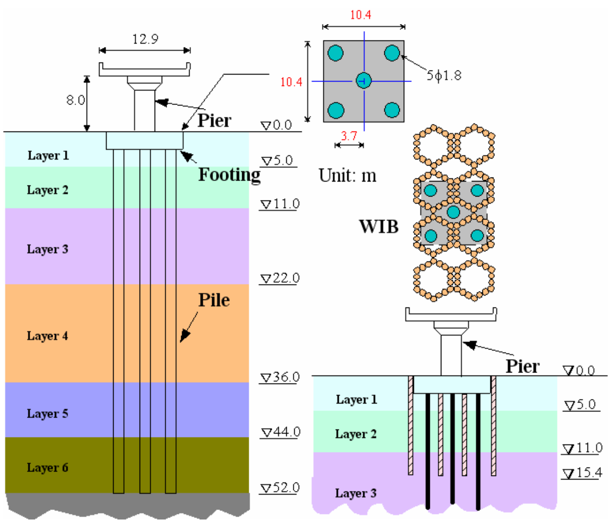
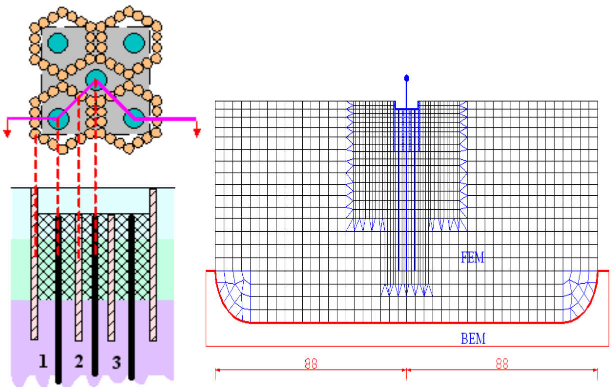


Figure 2. Taiwan shinkansen bridge foundation and the honeycomb-shaped WIB

3. DESCRIPTION OF STUDIED CASES

The Taiwan shinkansen bridge is illustrated as **Figure 2**. The pile foundation consists of 5 piles, and we imaginably take the model as surrounded by honeycomb-shaped WIB. The WIB consists of a multiple number of vertical soil-cement mixed columns, which are connected with each other and arranged in a shape of honeycomb cells in plan view. In order to simulate the interaction between structural piles and WIB in a 2-D model, the honeycomb shaped WIB is simplified as shown in **Figure 3 (a)** by considering the soil around the piles. The properties of the soil and the structures are listed in **Table 1** and **Table 2**. **Figure 3 (b)** shows the computation model. The WIB columns



(a) 2-D WIB (b) FEM-BEM model

Figure 3. Model of analysis

Table 1 Properties of the layered soil

Layer depth (GL-m)	Shear velocity (m/s)	Poisson ratio	Mass density (t/m^3)	Damping ratio (%)
(L1)5.0	122	0.485	2.0	5.0
(L2)11.0	172	0.491	2.0	5.0
(L3)22.0	231	0.489	2.0	5.0
(L4)36.0	279	0.486	2.0	5.0
(L5)44.0	331	0.480	2.0	5.0
(L6)52.0	376	0.474	2.0	5.0
∞	405	0.469	2.0	5.0

Table 2 Properties of the pile foundation and WIB

Pile:	Diameter	1.8 m
	Density	2.4 t/m^3
	Young's modulus	2.54E6 tf/m^2
WIB:	Density	2.0 t/m^3
	Poisson ratio	0.2
	Column thickness	1.0 m
	Shear velocity	1000 m/s

are discretized into solid elements, but they are connected by diagonal truss elements to take account of the shear resistant of honey-comb walls.

After the 1995 Hyogo-ken Nanbu earthquake, the Japanese codes were revised to take into consideration of devastating earthquake motions of the so-called Level II. In this study, the North-South component of the Hyogo-Ken Nanbu Earthquake record in Kobe (JMA-NS) is adopted as a typical excitation for such ground motion, and an artificially generated motion called S1-G1 is additionally used for a typical near-source earthquake. The predominant frequencies of these strong motions are respectively 1.46Hz and 0.8Hz.

Figure 4 shows the investigated cases in this paper. The original situation without any countermeasure is denoted by Case A (omitted for clarity). All the depicted cases in **Figure 4** use WIB as a measure for seismic mitigation, but with different design configurations. The WIB depth is

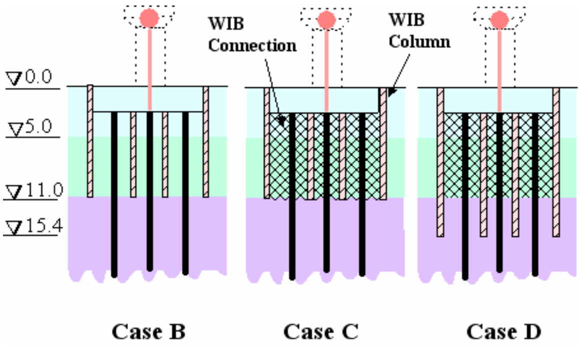


Figure 4. Studied cases of the foundation

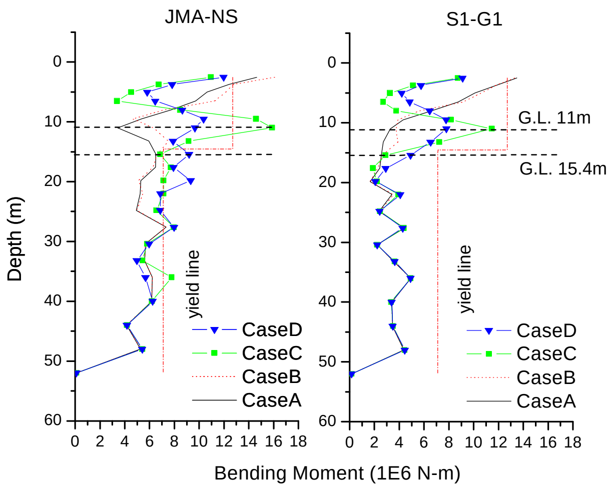


Figure 5. Maximum bending moment profile along depth

chosen between $1/b$ and $p/2b$ according to the Japan Highway Technical Center, where $1/b$ represents the characteristic length of an embedded pile. Case B assumes only several soil-cement walls below the footing, and the WIB walls are installed to reach G.L. 11 m. In contrast to Case B, Case C adds the diagonal truss elements between the walls to represent the shear resistance by WIB walls, which is the characteristic advantage of the honeycomb WIB. In Case D, the WIB walls are extended vertically down to G.L. 15.4 m and the properties vary gradually below G.L. 5m. From Case B to Case D, the WIBs are noted as optimized one by one. We can understand the performance of WIB thoroughly from the response comparison of those cases.

4. CALCULATION RESULTS

Figure 5 shows the maximum bending moment along the pile depth. These bending moments are picked up from the maximum values of all piles. The static yielding bending moment under the axial force is also provided for reference (vertical segmented line). From the static yielding bending moment line we can see the different reinforcement

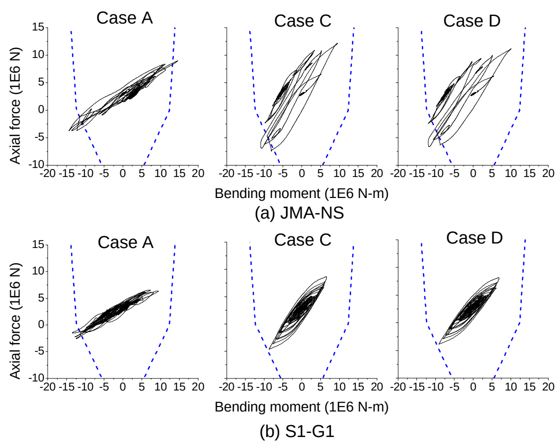


Figure 6. Bending moment-Axial force relationship at G.L.2.5m of pile 1

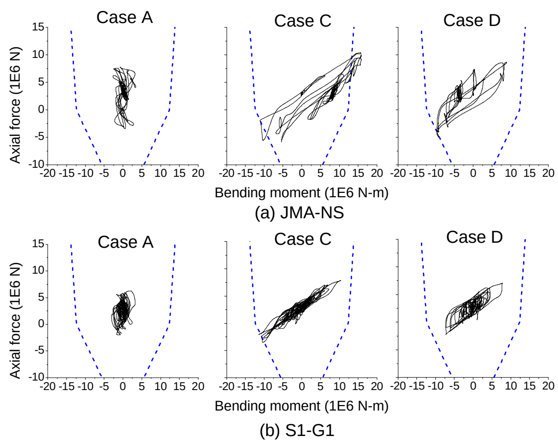


Figure 7. Bending moment-Axial force relationship at G.L.11.0m of pile 1

assignment by the portion of piles. The top 12 m portion of a pile is assigned with appropriate reinforcement (56 steel bars), and the rest is reinforced by a half of it for its relatively less internal forces. The bending moment response of Case B is quite close to the original Case A, and it shows only WIB walls do not influence seismic resistance much. Case C gives the effect of WIB connection, i.e. honeycomb shape arrangement. The peak value is reduced significantly, which means the honeycomb shape connection increases the horizontal stiffness significantly.

On the other hand, the pile internal force goes up abruptly and even exceeds that of the pile head at the bottom of WIB connection, which is not a desirable result. The reason is that the horizontal stiffness changes suddenly at that section. An effective way to reduce such effect is to make a smooth variation of the pile deformation along depth[1]. The WIB is modified according to this idea in Case D (**Figure 4**): the WIB columns are extended vertically to 15.4 m and the material of WIB gets softer proportionally from G.L. 5 m to the connection bottom (G.L. 11m). In this case, the shear velocity of WIB is set as 683 m/s below G.L.

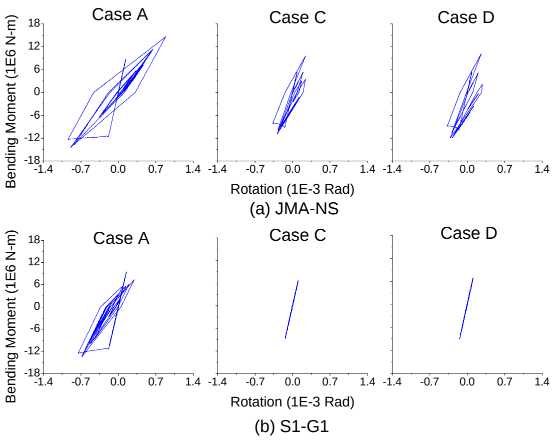


Figure 8. Bending moment-Rotation relationship at G.L.2.5m of pile 1

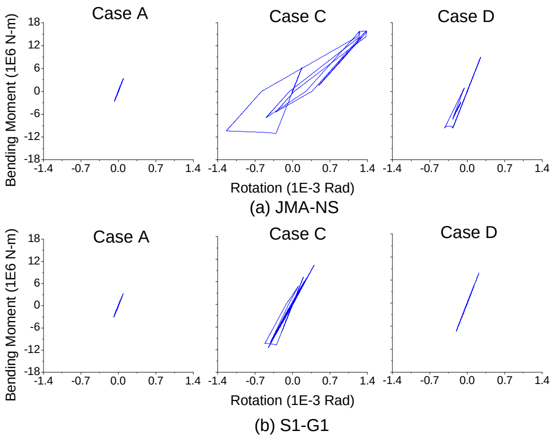


Figure 9. Bending moment-Rotation relationship at G.L.11.0m of pile 1

11m. The results show remarkable improvement in the modified WIB. The value at pile head does not change much, while that at the WIB connection bottom is diminished evidently to an allowable value.

In **Figure 6** and **Figure 7**, the interaction between bending moment and axial force is investigated at pile head and WIB bottom. The bending moment-axial force interaction curve of yielding point is depicted in the same figure for reference. Both of them show obviously that the well-designed WIB prevents the piles from failure by restraining the internal forces in a much safer zone. **Figure 8** and **Figure 9** illustrate the relationship between bending moment and rotation angle of pile 1. Case A leads to significant nonlinear behavior of the piles with the rotation increases at pile head, and Case C results in unfavorable response at the boundary of WIB connection. Case D reduces the internal forces at pile head and simultaneously avoids significant increase at crucial boundaries. From these results, the reinforcement steel bars in the top segment of piles can be lessened

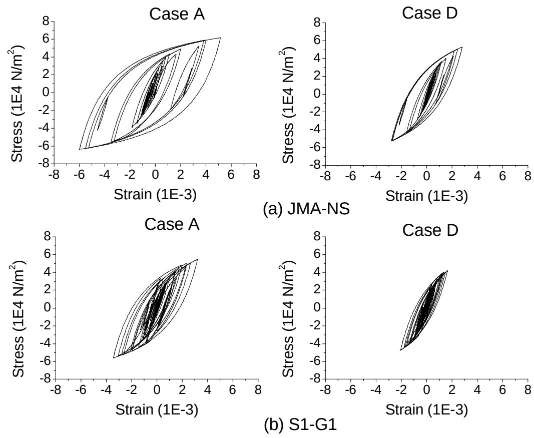


Figure 10. Stress-strain loops of a soil element below footing

for benefiting from the honeycomb WIB. **Figure 10** shows the stress-strain loops of the soil below the footing. It indicates that WIB restrains deformation of the inside soil to a substantial extent, which leads to the reduction of pile responses.

5. CONCLUSION

This paper investigated the application of honeycomb-shaped WIB to a Seismic Soil Pile Interaction system. From the results, the WIB countermeasure is validated to be an effective method for anti-seismic design. It can reduce the internal forces of piles significantly. However, it is further needed to design the WIB properly for a specific foundation. The depth of the WIB has great influence on responses, because the WIB improves the horizontal impedance locally so that large bending moments may occur at the boundaries of WIB or its connections. An optimized WIB should keep the internal forces at several critical points in much safer zone, which can be easily achieved step by step.

REFERENCES

1) Takemiya, H. and Shimabuku, J.:Application of soil-cement columns for better seismic design of bridge piles and mitigation of nearby ground vibration due to traffic, *Journal of Structural Engineering, JSCE*, **48A**, 437-444, 2002.
2) Hardin, B.O. and Drnevich, V.P.: Shear modulus and damping in soils: design equations and curves, *Journal of the Soil Mechanics and Foundations Division, ASCE*, **98**, SM7, 667-692, 1972.
3) Giberson, M.F.: Two nonlinear beams with definitions of ductility, Journal of the Structural Division, *Proceeding of the American Society of Civil Engineers*, **95**, ST2, 137-157, 1969.
4) Shimabuku, J. and Takemiya, H.: Nonlinear soil-pile foundation interaction analysis based on FEM-BEM hybrid technique, *Proceedings of the 25th JSCE Earthquake Engineering Symposium*, Tokyo, Japan, 461-464, 1999.

(Received October 10, 2003)