Comparison of modeling methods of drilled shaft foundation for seismic design

Kyung-Soo Jeon, Kyoung-Bong Han, Joo-Yeob Seong & Pil-Young Song
Super Long Span Bridge R&D Center, Korea Expressway Corporation, Hwaseong-si ,Gyeonggi-do,Repubilic of Korea

2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
A bent foundation with single drilled shafts is faster in construction and more economical than a foundation with a footing in South Korea, which has good rock in a shallow depth. Methods to model soil reaction on drilled shafts without a footing are equivalent cantilever, equivalent base spring and equivalent soil spring. The behaviors of drilled shafts are very sensitive to soil's lateral reaction in seismic design. In this paper, six single drilled shaft piers with 1m diameter were constructed, and reduced diameter shaft above the ground and shaft having the steel casing under the ground were constructed to induce plastic hinge to occur above the ground. Cyclic and simple lateral load tests loaded at 4m above the ground were taken to examine the lateral behaviors. Simplified soil models such as linear elastic springs and p-y curve springs were adopted, and pushover analyses were made considering nonlinear behavior of reinforced concrete. The analysis results were compared with test results. The most popular bridge, a pre-stressed concrete beam girder, in South Korea was chosen, and displacements and stress of drilled shafts with two soil models were compared.

RÉSUMÉ
Une fondation pliée avec puits foré seul est plus rapide pour la construction et plus économique que d'une fondation avec un pied en Corée du Sud, où de bonnes roches existent dans une faible profondeur. Les méthodes pour modéliser la réaction du sol sur des puits forés sans pied sont en porte à cantilever équivalent, ressort de base équivalent et ressort du sol équivalent. Les comportements des puits forés sont très sensibles à la réaction latérale des sols dans la conception parasismique. Dans cet article, six piles de puits foré seul avec un diamètre de 1 m ont été construits, et la réduction de diamètre d'axe au-dessus du sol et de l'arbre ayant l'enveloppe en acier dans le sol ont été construits pour induire charnière en plastique de se produire au-dessus du sol. Cycliques et simple des tests de charge latérale chargés à 4 m au-dessus du sol ont été pris pour étudier le comportement latéral. Modèles de sol simplifié comme ressort élastique linéaire et des ressorts de courbe p-y ont été adoptées, et une série d'analyse push-over ont été prises en tenant compte le comportement non linéaire du béton armé. Les résultats d'analyse ont été comparés avec les résultats des essais. Le pont le plus populaire, une poutre en béton précontrainte, en Corée du Sud a été choisi, et déplacements et contraintes de puits foré de deux modèles de sol ont été comparés.

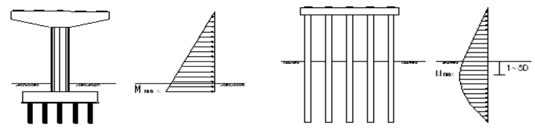
1 INTRODUCTION

Single drilled shafts are very economical foundation of bridges because they do not need to construct a footing. A footing can be a fixed point under seismic behavior, and maximum bending moment occurs on the upper portion of a footing. However, bending moment of a drilled shaft pier is not concentrated like columns above the footing because it has no big difference of stiffness. Soil's lateral resistance below the ground surface has an important role to determine bending moment and lateral displacement. Soil's lateral reaction has a nonlinear relation with displacement of soil. A linear relationship is proposed to predict the behavior of bridges with small displacement, but nonlinear relationship between soil's reaction and displacement has to be considered under large lateral displacement. However, considering nonlinear relationship is very difficult in designing common bridges such as pre-stressed beams and box girders. Six drilled shaft piers with 1m diameter are constructed in the sandy ground and laterally loaded at 4m above the ground to study lateral behaviors of the piers. Test results are compared with prediction by linear soil springs, which come from Korea Road Bridge Design Specification (KRBDS), Federal Highway Administration (FHWA) and nonlinear soil spring which represents p-y curve. Seismic design results with two soil models are analyzed supposing linear and nonlinear stress strain relationship of reinforcing concrete.

2 SINGLE DRILLED SHAFT PIER

2.1 Characteristics of lateral behavior

A substructure having a footing has a maximum moment above a footing under seismic force because the footing has a role as a fixed point, and a plastic hinge occur at the point irrelevantly to the magnitude of soil's lateral reaction. Drilled shaft piers without a footing have no significant stiffness difference, and moment concentration is much less than the substructure with a footing. Soil's lateral reaction has an important role on moment distribution of drilled shaft piers. Maximum moment point usually occurs under the ground surface in the depth of 1~3D shown in figure 1 and varies according to soil's reaction. Soil's reaction has an important effect on substructure design results of bridges. Modeling methods of drilled shaft piers are equivalent cantilever model, equivalent base spring model and equivalent spring model. For an equivalent cantilever model, three possible fixed points such as zero displacement point, maximum negative displacement point and maximum moment point are supposed, and a fixed point is determined by iteration.

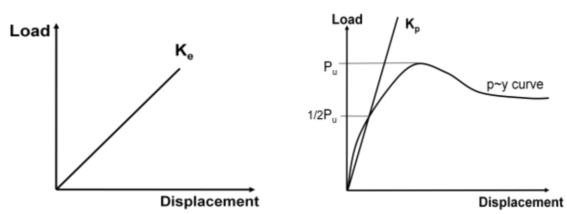


a) Substructure with footing b) Substructure with drilled shaft pier

Figure1. Moment Distribution

2.2 Soil spring

Linear relationship between lateral displacement and lateral reaction which is proposed by Chang (1937) is adopted in KRBDS (2008), and a governing equation is equation [1]. FHWA (1986) recommends p-y method to predict lateral behaviors of drilled shaft piers. For a practical purpose, linear relationship shown in figure 2 is proposed within 25mm displacement, and nonlinear relationship should be considered under larger displacement from FHWA (1986). If a bridge was shaken due to seismic force, drilled shaft foundations would push or pull the surrounding soil. The soil has no resistance for pulling force, and gap model is needed to depict no pulling force. Figure 3 shows nonlinear soil model with a gap element which does not resist tension.



a) KRBDS(2008) b) FHWA(1986)

Figure2. Soil Spring Model.

$$\delta = \frac{(1+\beta h)^3 + 1/2}{3EI\beta^3} P \qquad [1]$$

Where,

β : $\sqrt[4]{\frac{k_H \bullet D}{4EI}}$

k_H : $k_{HO}\left(\frac{B_H}{30}\right)^{-3/4}$

$B_H = \sqrt{D/\beta}$,

k_{HO} : $\frac{1}{30}\alpha E_s$

δ : lateral displacement of pier

P : lateral force

h : distance between the ground and loading point.

E : Elasticity coefficient of pier

I : Second Moment Inertia of pier,

D : Diameter of pier

E_s : Soil's elasticity,

α : Coefficient according to test method

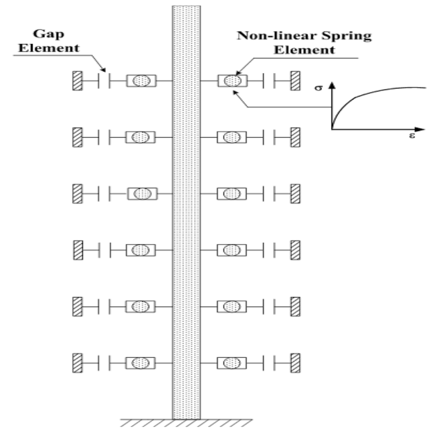


Figure3. Soil model with gap element

2.3 Test Pier

Six drilled shaft piers shown in figure 4 were constructed in Incheon, which is 20km west away from Seoul for lateral load tests. The ground consists of silty sand and highly weathered rock shown at Table 1. Uniaxial strength of the concrete is 45MPa, and the diameter of pier below the ground is 1m. To induce a plastic hinge above the ground, the diameter of two piers above the ground is 0.85m, and two piers have steel casings whose thickness and diameter are 10mm and 1m from the ground to 3m depth respectively. Lateral loads were applied at 4m above the ground to depict lateral load behaviors of a column of a bridge like figure 5 and picture 1. Table 2 shows lengths, diameters and test methods of test piers. Simple means one directional load test, and cyclic means pushover load test.

Table 1. Ground Survey Result

Depth(m)	N Value	Description
1.5	6	Silty Sand
3.0	6	Silty Sand
4.5	7	Silty Sand
6.0	11	Silty Sand
7.5	33	Silty Sand
9.0	100	Silty Sand
10.5	68	Highly Weathered Rock
13.0	100	Highly Weathered Rock
14.5	125	Highly Weathered Rock
16.0	150	Highly Weathered Rock
17.5	375	Highly Weathered Rock
19.0	375	Highly Weathered Rock

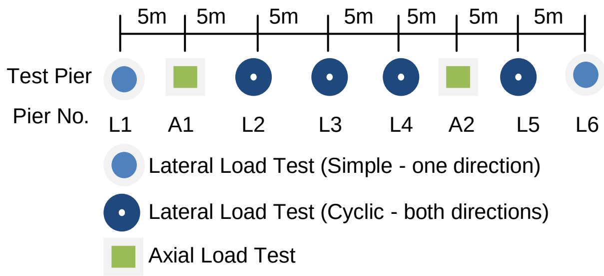


Figure 4. Test Pier Arrangement

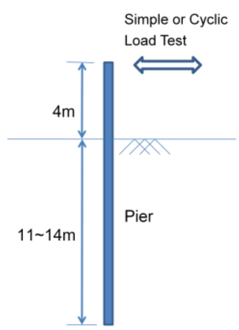


Figure 5. Schematic Lateral Load Test

Picture 1. Lateral Load Test

Table 2. Test Pier and Loading method

Pier No.	Below the ground(m)		Above the ground(m)		Lateral Loading Method
	Diameter	Length	Diameter	Length	
L1	1 (Casing*)	11	1	4	Simple (one direction)
L2	1	12	0.85	4	Cyclic (both directions)
L3	1	12	1	4	Cyclic (both directions)
L4	1	12	0.85	4	Cyclic (both directions)
L5	1 (Casing*)	14	1	4	Cyclic (both directions)
L6	1	11	1	4	Simple (one direction)

*: Length=3m, Thickness=10mm

2.4 Comparison between test and prediction results

Figure 6 shows a test result and prediction results, which are predicted from KRBDS (2008), FHWA (1986) and p-y method. Prediction results of KRBDS (2008) and FHWA (1986) supposing EI constant overestimate lateral resistance over 36mm displacement at the ground. The prediction result of p-y method, which considers nonlinear relationship of concrete and reinforcement provided by LIPLE Plus, underestimates the lateral resistance. To predict the lateral behavior of a pier, p-y method is more reasonable than KRBDS (2008) and FHWA (1986). Figure 7~12 show the comparison between test and prediction results by SAP 2000 applying nonlinear model for concrete and reinforcement and gap model for tension cracks of soil. One of two prediction results in Figure 7 and Figure 11 is predicted supposing complete bonding between concrete and a steel casing, and the other is derived on the slipping condition. The prediction curves between 50mm and 150mm displacement have a large gap compared with each test result. That means smooth surface of the steel casing cannot make enough bonding, and some measures are needed to ensure secure bonding between steel and concrete. The node distance is varied in 0.25m, 0.5m and 1.0m, and soil's lateral reaction is depicted with p-y curve. It is proved that the smaller node distance is, the closer the prediction result is to the test result. However, the difference is small. Prediction difference of Pier L6 between Figure 6 and Figure 12 comes from the difference between nonlinear models of concrete and reinforcement provided by LPILE Plus and SAP 2000. Through the comparison between test results and prediction results of SAP 2000, it is proved that concrete and soil should be modeled as nonlinear relationship to predict large lateral displacement correctly.

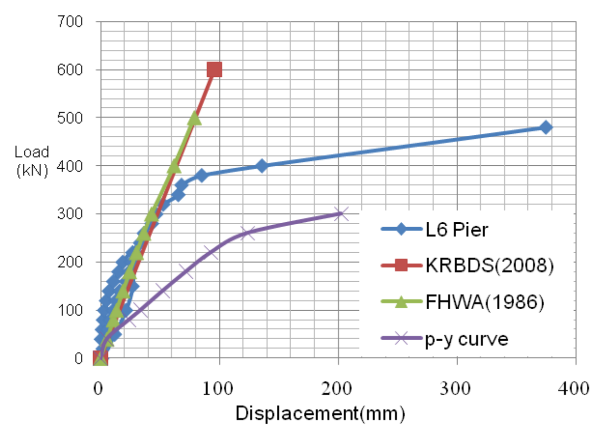


Figure 6. Comparison between L6 pier and prediction results

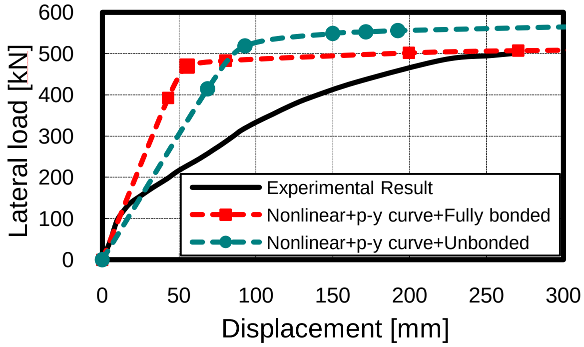


Figure 7. Comparison between L1 pier and prediction results

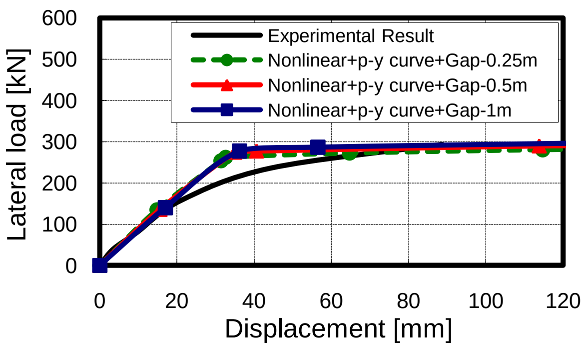


Figure 8. Comparison between L2 pier and prediction results

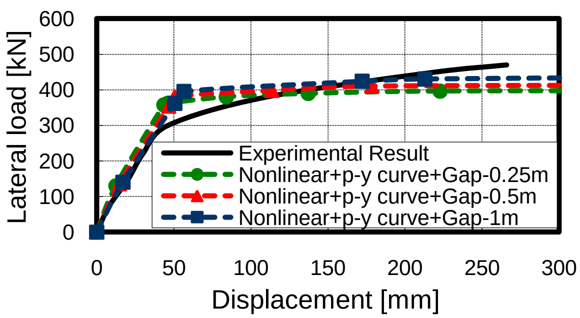


Figure 9. Comparison between L3 pier and prediction results

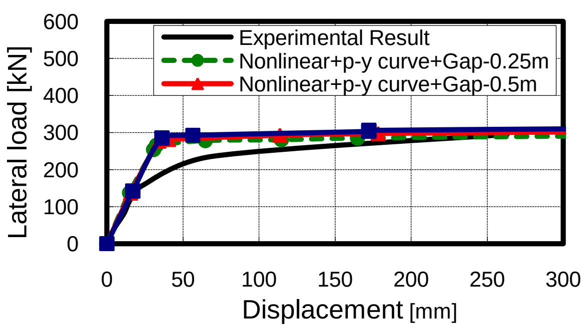


Figure 10. Comparison between L4 pier and prediction results

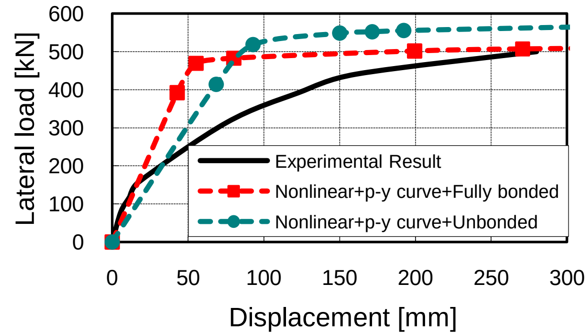


Figure 11. Comparison between L5 pier and prediction results

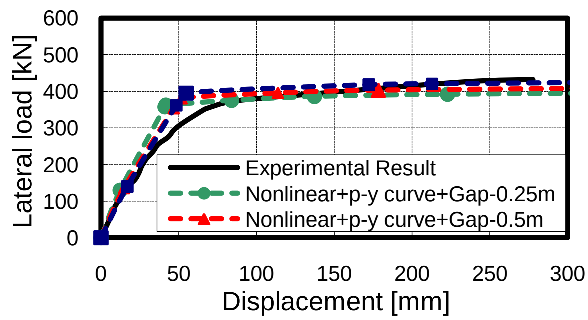


Figure 12. Comparison between L6 pier and prediction results

3 BRIDGE DESIGN RESULT

3.1 Bridge and Seismic Wave

A prestressed beam girder of which main span length is 25m was chosen, and time history analysis was taken according to scale downed El Centro wave of which maximum acceleration is 0.154g. Fig 13 shows a drawing of the bridge. Foundation of the bridge consists of five drilled shaft piers of which diameter is 1.2m. Liner spring derived by FHWA (1986) and p-y curve spring are chosen to depict soil's lateral reaction under seismic force. Linear spring for soil reaction was considered on the condition of elastic and non-elastic behavior of concrete and steel, and p-y curve is chosen on the condition of elastic behavior. Table 3 shows the soil, concrete and steel models to analyze the behavior of the bridge by SAP 2000.

Table 3. Models of soils, concrete and steel

Model	Soil	Concrete and steel
Model 1	Linear Spring by FHWA(1986)	Linear stress strain relationship
Model 2	Linear Spring by FHWA(1986)	Nonlinear stress strain relationship
Model 3	p-y curve	Linear stress strain relationship

3.2 Analysis result

Figure 14 and 15 show bending moments occurred at the ground and 1m below respectively. The magnitude of bending moment at the ground and 1m below is in the order of Model 2, Model 3 and Model 1. The magnitude of shear force at 1m below the ground in figure 16 is in the order of Model 3, Model 2 and Model 1. Model 3 and Model 2 have no big difference in shear force at the ground and Model 1 has smallest shear force in figure 17. It can be concluded that the shear force difference between at and below the ground comes from soil's reaction. The deflection at the top of coping had no big difference between model 2 and model 1, and a little smaller deflection occurred in model 1 in figure 18. Model 3 gives us good results in the analysis, but Model 3 needs a lot of computing time because of nonlinear models of concrete and steel.

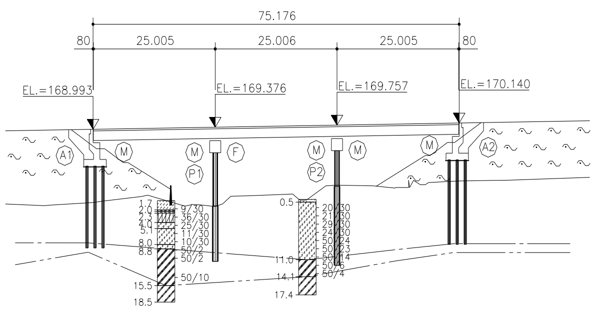


Figure 13. Drawing of a sample bridge

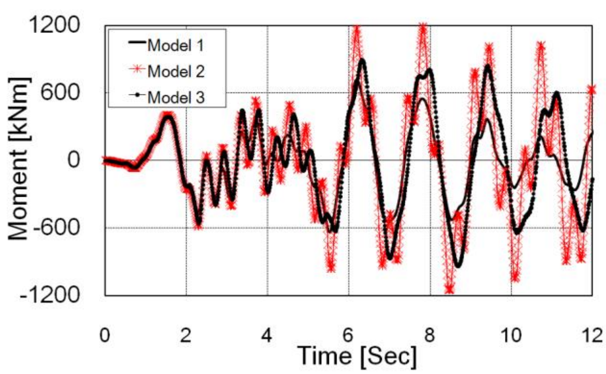


Figure 14. Moment at 1m below the ground

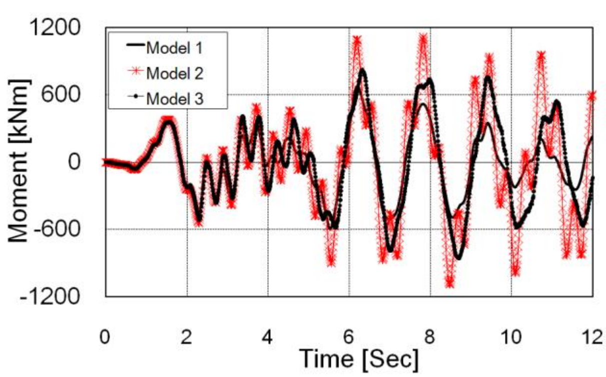


Figure 15. Moment at the ground

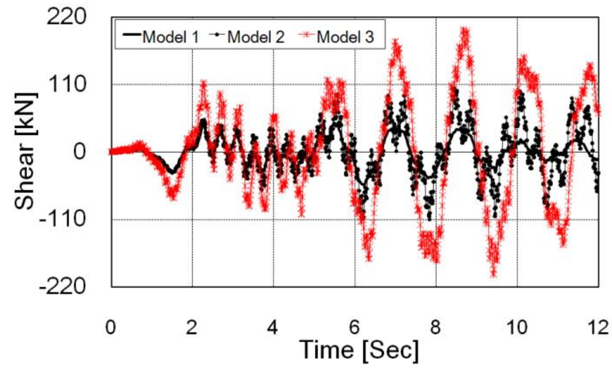


Figure 16. Shear force at 1m below the ground

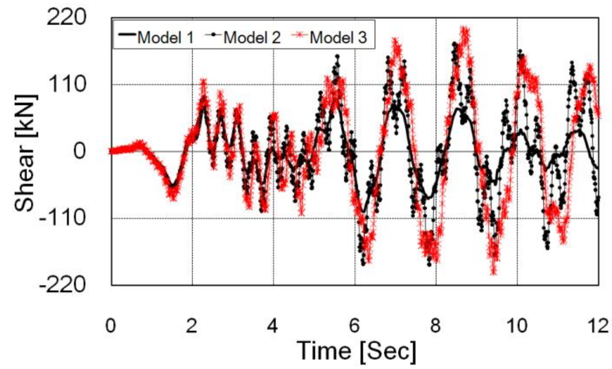


Figure 17. Shear force at the ground

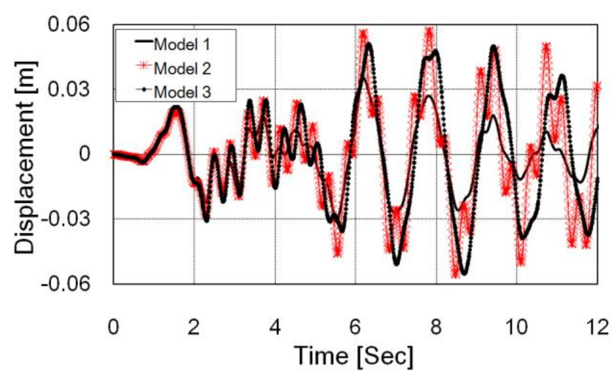


Figure 18. Displacement at the top of the coping

4 CONCLUSION

The followings are acquired through the lateral load tests and the sample bridge design.

1) Linear spring to depict soil's lateral behavior such as KRBDS (2008) and FHWA (1986) predicts lateral resistance conservative in small displacement but overestimates it in large displacement.

2) P-y method should be applied to get an accurate prediction in small and large displacement, and gap element could give more accurate estimation.

3) To predict the behavior of a drilled shaft having a steel casing to prevent a plastic hinge under the ground, additional study is needed.
4) Model 2 predicts the largest moment due to nonlinear stress strain relationship for reinforced concrete, and model 3 predicts the largest shear force because of no consideration of tension crack in concrete.
5) Model 3 can be a reasonable modeling method to predict bridge behaviors under maximum acceleration, 0.154g.

References

FHWA (1986), "Seismic Design of Highway Bridge Foundations" Federal Highway Administration, Report in 3 Volumes: FHWA/RD-86/101, FHWA/RD-86/102, and FHWA/RD-86/103

FHWA (1996). "Seismic Design Course Design Example No. 6." U.S. Department of Transportation Federal Highway Administration

FHWA (1987). "Seismic Design and Retrofit Manual for Highway Bridges." Report No. FHWA-IP87-6, Federal Highway Administration, National Technical Information Service, Springfield, VA

FHWA (1986). "Seismic Design of Highway Bridge Foundations. (Example Problems and Sensitivity Studies)" Report No. FHWA-RD86/103, Federal Highway Administration, National Technical Information Service, Springfield, VA

FHWA (1986). "Seismic Design of Highway Bridge Foundations Vol. II" FHWA/RD-86/102,

Reese, L. C. and K. J. Nyman, (1978), Field Load Test of Instrumented Drilled Shafts at Islamorada, Florida, a report to Girdler Foundation and Exploration Corporation, Clearwater, Florida.

Korean Society of Civil Engineers (2008),”Korea Road Bridge Design Specification”