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# Integral Abutment Bridges-Development of Soil Model for Soil Structure Interaction in Time History Analysis

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**Abstract**: - Integral abutment bridges are defined as bridges with no joints between the superstructure and the supporting abutments. The loads on laterally applied bridges are mostly worked via a row of perpendicular piles which are established underneath the abutment wall. The response of the soil compiled behind the abutment and exactly adjacent to the foundation is said to be the most significant source of uncertainty affecting the analysis and design of integral abutment bridges. Clay stiffness, hard, medium and low around the piles and level of sand compaction, dense, medium and loose state of the abutment backfilling are parameters that show the effect of soil in performance of integral abutment bridges. Nonlinear time history analysis on two-dimensional integral abutment bridges under seismic loads were performed with finite element software. Under seismic loading, it is proposed that dense backfilling of the abutment reduces deflection of the pile, the displacement of the abutment, the moments in the girder and especially the pile head moments. When there is seismic loading, with the piles grounded in hard clay, there is decrease in the abutment displacement, while the greatest girder moment, the maximum pile moment and the maximum girder moment at the abutment will be reduced. Low clay stiffness around piles minimizes pile lateral force at pile head and hard soil stiffness around piles minimizes pile head abutment displacement.

**Keywords:** - Integral Abutment Bridges, Time History Analysis, Clay Stiffness, Seismic Loading, Compacted Backfilling.

## I. INTRODUCTION

The structural elements of typical abutment in integral abutment bridges usually consist of an abutment wall, two wing walls, and several supporting piles, as shown in Fig1. Approach slabs, which are cast integral with the abutments, increase the mass considerably and have good effect on seismic performance. The advantages of these bridges include increased structural capacity during seismic events [1], reduced maintenance costs compared to jointed bridges with expansion joints and abutment bearings, reduced corrosion and material degradation at the joints [2], and easy construction. The soil's stiffness has a significant effect on load distribution when the soil, piles, abutment, and superstructure act as a combined system to resist the loading on the bridge [3]. When the integral abutment bridges are analyzed and designed, the nonlinear soil-abutment and soil-pile interaction are usually the greatest uncertainties. This due to the scale and type of soil as well as the interdependence of the deformations and stresses [4]. When a pile supporting an integral abutment is laterally displaced, moment is induced along the length of the pile. The induced moment warrants the consideration of axial load-moment interaction when determining the capacity of the pile. Unlike conventional single span bridges where seismic forces are neglected, there is a need to consider seismic behavior in single span bridges with integral abutments to help design the buried abutment piles [5]. The superstructure and substructure move into and away from the backfill when subjected to lateral loading. It is generally recognized that any lateral movement of the bridge deck in the direction of the abutment during an earthquake exerts a strong lateral force to the abutment that triggers a strong resistance in the soil backfill and the outcome is a permanent displacement of the soil. In seismic design [6], [7] an abutment system relies on the soil backfill to provide resistance to longitudinal bridge deck displacement.

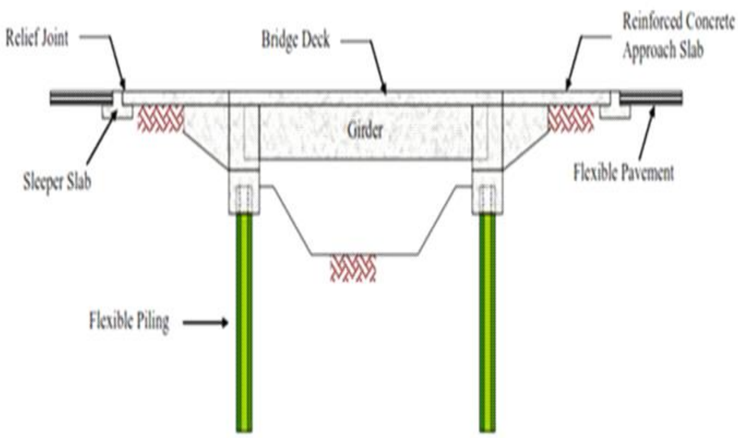


**Fig.1 Typically of Integral Abutment Bridges with HP pile**

Including this abutment contribution in seismic bridge design may reduce the pressure on the bridge foundation. Passive earth resistance at the abutments may limit earthquake induced bridge deck displacements. During strong shaking, if the deck impacts the abutment, the backwall can break off into the backfill. The soil reaction forces which are distributed on the wall are found to be nonlinear in nature, and show discrepancy with depth, degree and mode in the wall displacement. The lateral movement of the pile is mainly a function of horizontal soil stiffness. The response of the soil compiled behind the abutment walls and exactly adjacent to the piles is said to be the most significant source of uncertainly affecting the analysis and design of the integral abutment bridges. During the lateral extension of the bridge system, on the other hand, the degree of soil pressure is expected to be highly significant, which in turn can seriously influence the general structural scheme of the bridge-wall-pile system. Parametric study was carried out for the response of laterally loaded piles supporting the abutment of the integral abutment bridge under various conditions. Two-dimensional model of an integral abutment bridge with soil springs around the piles and behind the abutments was constructed with finite element ANSYS. 2D finite element models for the simple span are set up to explore the nonlinear responses of integral abutment bridge subjected to time history seismic loads. Clay stiffness, hard, medium and low, around the piles and level of compaction sand, dense, medium and loose, of the abutment wall backfilling are parameters that show the effect of soil in performance of integral abutment bridges. Nine bridge cases with combined clay stiffness around piles and compacted backfill were modeled by ANSYS to show which combination soils deliver good performance under seismic loads. Soil-backfill interaction, abutment-backwall connection and soil-pile interaction are main issues in modeling integral abutment bridges.

## • PARAMETRIC STUDY

As mentioned above an integral abutment bridge acts as a rigid structure and when applied to lateral displacement, moves into or away from backfill. Soil around backfill and adjacent pile has a main role in the performance of integral abutment bridges. With the detailed properties of backfill and soil around pile determined, this research involves nine case studies to analyze the list in Table 1. Parametric study considers the properties of the backfill and variations in the soil around the pile. Loose, medium and compacted sand behind the abutment is considered to determine how the compacted backfill as well as hard, medium and low clay stiffness chosen for around pile can affect bridge performance in lateral displacement.

**Table.1: Combination of Soil around Pile and Backfill**

| ID case | Soil around pile (clay) | Soil around pile (sand) |
|---|---|---|
| 1 | Hard | Dense |
| 2 | | Medium |
| 3 | | loose |
| 4 | Medium | Dense |
| 5 | | Medium |
| 6 | | loose |
| 7 | low | Dense |
| 8 | | Medium |
| 9 | | loose |

## II. MODEL DESCRIPTION

A selected structure bridge in Pennsylvania chosen for modeling is a straight integral abutment bridge I-99 near Port Matilda in a moderate earthquake hazard zone. Length of this bridge is 18.7 m with 3 m height of abutment. A single row of weak axis oriented HP12×74 piles support the abutment. Table.2 summarizes the material and section properties of the superstructure cross-section comprising four precast concrete girders with concrete compressive strength MPa. Piles length is 6.26 m and 4.5 m.

**Table.2: Material and Section Properties for 2D Models**

| Bridge | Components | Modulus of Elasticity Mpa | Area | Moment of Inertia |
|---|---|---|---|---|
| Superstructure | | 35,536 | 4.37 | 1.432 |
| Substructure | Abutment | 21,760 | 16.80 | 2.081 |
| | Backwall | 25,124 | 16.80 | 2.081 |
| | Pile(Abutment1) | 200,000 | 0.155 | 8.52E-4 |
| | Pile(Abutment2) | 200,000 | 0.127 | 6.97E-4 |

## III. FORCE-DEFLECTION CURVES FOR SOIL BEHIND BACKWALL

P-y curves, which describe the relationship between the lateral soil pressure (horizontal force per unit length) and the corresponding lateral displacement, is the method used in this soil modeling. The classical p-y curve method is adopted to provide a load-deformation curve of laterally loaded soil-structure interaction behaviors. Dynamic p-y examines the method employed in analyzing how the piles respond dynamically to seismic activity. This will provide a better understanding of how the properties of the soil can be varied in terms of depth, nonlinear soil behavior, and nonlinear behavior of the interfacing of pile and soil as well as prior research. Ross W. Boulanger [8] offers experimental evidence to support using dynamic p-y analysis in attempting to address the problems arising from the interaction of the soil's structure under seismic conditions. Test data derived from work done at Brigham Young University proposed that the abutment wall be backfilled with cohesion less sand [9]. Properties of three types of backfill are tabulated in Table 3. Soil-structure-backfill interaction is shown in **Fig 2.**

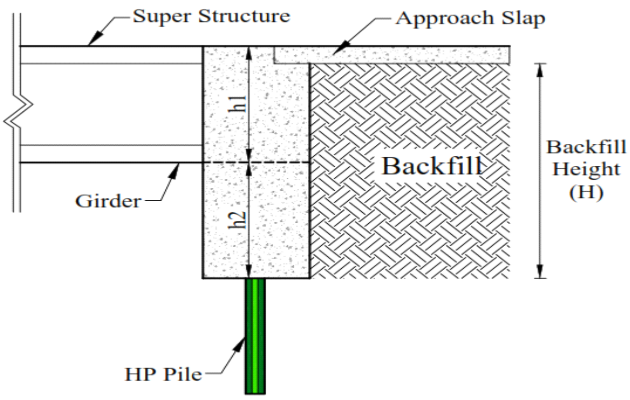


**Fig.2: Soil Backfill in Integral Abutment Bridge**

**Table.3 Soil Properties behind Abutment**

| Property | Units | Dense | Medium | Loose |
|---|---|---|---|---|
| Density () | | 19.3 | 18.7 | 18.2 |
| Angle of Friction() | Degree | 37.4 | 34 | 30.6 |

To obtain the seismic passive earth pressure as p-y curves, a log spiral procedure are employed according to Shamsabadi et al [10] or NCHRP12-70 [11]. Shamsabadi et al conducted a detailed investigation on the interaction of nonlinear soil-abutment in bridge seismic design and proposed a simplified hyperbolic relation of force displacement as shown by Equation1:

**(1)**

Where is the lateral displacement of abutment, K is average soil stiffness, is maximum abutment force per unit length of the wall developed at a maximum displacement of and determined by Equation 2.

**(2)**

On the basis of the bridge location, peak ground acceleration (PGA) and horizontal seismic coefficient K are obtained. Then, a log spiral procedure utilizing the NCHRP figures is employed to determine the different abutment backfilling soils. Here in PGA, the choice is 0.39g and horizontal seismic coefficient for compacted sand is 4, medium sand is 3.5 and loose sand is 3 in soil density while h is abutment height. On the basis of the findings of the Brigham Young University experiment for dense sand backfilling, and for loose sand, h is 3 m and is the height of the pile cap. Considering the test results, for 3 m abutment height, K is 307 kN/cm/m assigned for dense backfilling and 204 kN/cm/m for loose backfilling. Following the above approach, force displacement relations for unit length of the wall for dense, medium and loose sand backfilling was determined as shown in Fig 3 and modeled by nonlinear spring elements in the bridge finite element modeling.

**Fig.3: P-y curve per unit length for 3 m abutment**

## IV. ABUTMENT BACKWALL CONNECTION

For moment-curvature relation in abutment-backwall connection, strain compatibility approach is used with Whitney's equivalent stress block for computing ultimate moment capacities that are shown in Fig 4. In this modeling as shown in Fig 5, connection between backwall and abutment used PeenDOT standard [12]. Due to the unequal reinforcement arrangement and an effective concrete width of the abutment-backwall connections, calculated strength and its initial stiffness of these connections are subjected to expansion movements, which are different from those subjected to contraction movements by a factor of approximately 1.2. In addition, the calculated initial rotational stiffness for abutments is 16 to 20 times higher than those of abutment-backwall connections, clearly indicating the connection's weakness. Conversion from moment curvature relationship, Fig 6, to moment-rotation relationship M-θ is required to determine the hinge between abutment and backwall element properties. Based on the assumption of small deformation and constant moment over a joint length (L), this conversion can be written as Equation 3:

**(3)**

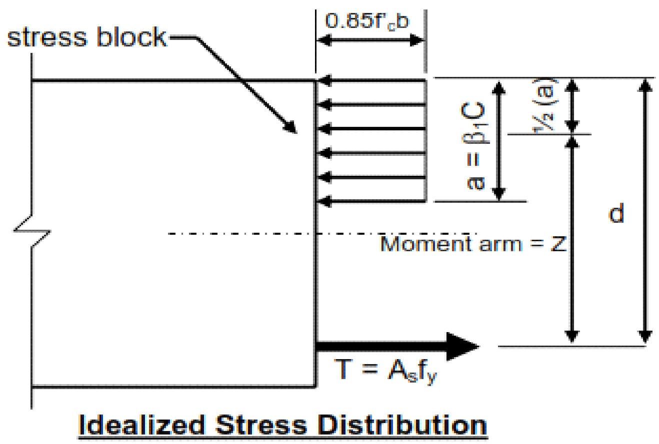


**Fig.4: Whitney's equivalent stress block**

According to Paul [13], the joint length, L, is associated with the development length of an epoxy-coated reinforcement, which is equal to 0.4 m based on AASHTO. By assuming a linear variation of rebar stresses over the development length, with a fully mobilized stress at the one end and zero stress at the other end, one half of the development length was used as the joint length, L = 0.2 m.

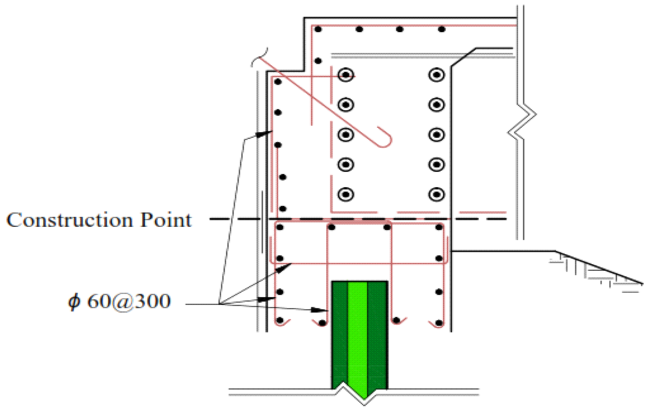


**Fig.5: Penn DOT Standard for Integral Abutment Details**

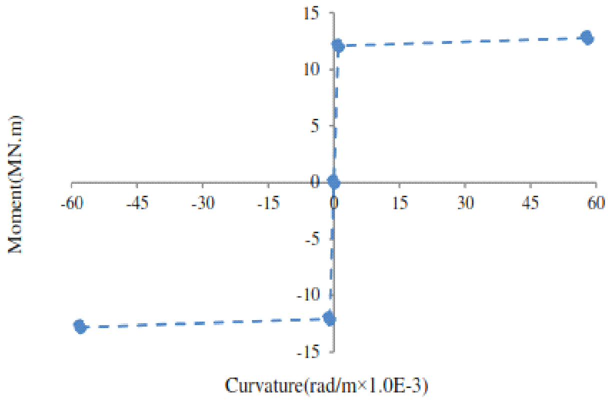


**Fig.6: Moment Curvature Relation for Penn DOT Detail**

## V. FORCE- DEFLECTION CURVES FOR SOIL AROUND PILES

Piles supporting integral abutments are not laterally loaded, but laterally displaced. The lateral displacement is a result of lateral expansion or contraction of the superstructure and all resulting forces are a function of pile stiffness, rotational restraint of the pile head, pile embedment depth, lateral displacement, and soil stiffness. Three different clay properties, hard, medium and low values for soil-pile interaction have been developed with respect to the different overburden pressures. To cover a practical range of soil properties, consideration of previous research [14] allowed for the determining of representative values. The assumed hard and low clay stiffness properties are tabulated in Table 4.

**Table.4: Soil Properties and Range Determination**

| Property | Units | hard | medium | Low |
|---|---|---|---|---|
| Clay density | | 22 | 19 | 16 |
| Elastic modulus | | 353 | 271 | 190 |
| | mm | 0.13 | 0.2 | 0.25 |

For nonlinear spring modeling the API methods are based on the study of the p-y curves constructed by Matlock for soft clay, Reese for stiff clay, and O'Neill [15] for sands. This method will be described and will adopt in the following study.

**(4)**

Where is ultimate lateral soil resistance corresponding to ultimate shear stress of soil, is the effective unit weight, X is the depth from ground surface, is the undrained shear strength of the clay, and J is a constant frequently taken as 0.5 determined by Equation 5.

**(5)**

Clay is commonly used around the pile and selection of the characteristics of medium and hard clay is based on the geotechnical reference [16] so as to be representative of soil characteristics. Table 4 shows the three varying soil cases as defined for the sensitivity study and Fig 7, 8, and 9 show p-y curves for hard, medium and low clay that are defined as nonlinear springs for soil properties in finite element modeling.

**Fig.7: P-y curves for hard clay**

**Fig.8: P-y Curves for Medium Clay**

**Fig.9: P-y Curves for low Clay**

## VI. FINITE ELEMENT MODELING

For modeling 2D integral abutment bridge with finite element software ANSYS, COMBIN39 element was used for soil-pile interaction and soil-abutment interaction. COMBIN39 is a unidirectional element with nonlinear generalized capability to force deflect that can be used in any analysis. One degree of freedom was used for these elements because only lateral movement is of particular interest. The structure of bridge composite slab, girder section, abutment, backwall, and piles were combined and modeled using a BEAM3 element. BEAM3 is a uniaxial element with tension, compression, and bending capabilities (see Fig 10). Time history displacement that is simulated from the Port Island in the 1995 Hyogoken Nambu (Kobe) earthquake in Japan is defined as a lateral displacement at support nodes on each side of the piles. The bridges are studied using the Port Island in the 1995 Hyogoken Nambu (Kobe) earthquake, shown in Fig11, scaled to the PGA of 0.39g with ERRA. Nonlinear time history analyses were done by applying the scaled components of the Kobe earthquake on the bridge in the longitudinal direction.

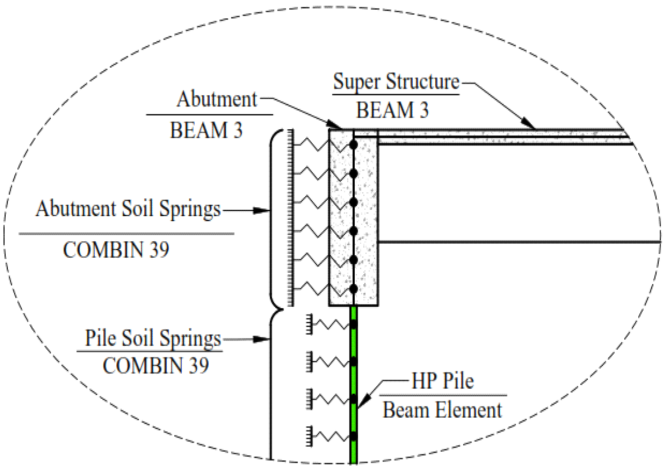


**Fig.10: Finite element modeling with ANSYS**

**Fig.11: Time History Displacement in Soil Profile during Event 0.39g in 2m Depth**

## VII. RESULT AND DISCUSSION

In evaluating the effect of various types of clay surrounding the piles with different compacted sand at the backside of the abutment in dynamic analysis of the integral abutment bridge, time history analysis was done with the use of the 2-dimensional finite element model of the bridge for the nine cases presented in Table 1. Nonlinear time history analyses were done with the application of the scaled component of the KOBE earthquake in the longitudinal direction of the bridge. The specific locations of critical responses appear in Fig

12. Critical responses of pile head lateral force (), pile head displacement (), pile head moment () and girder axial force () are determined in Table 5.

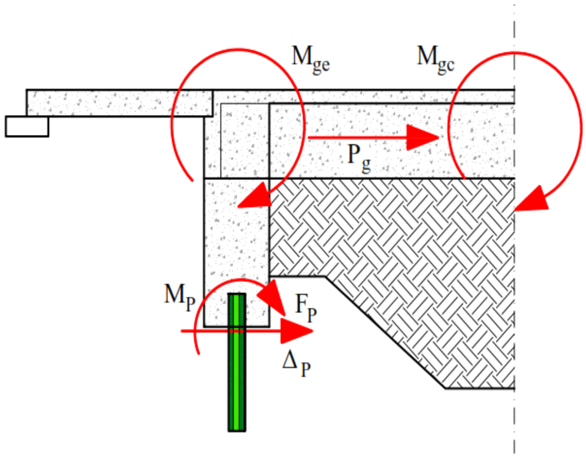


**Fig.12: Specific location in integral abutment bridge**

Maximum moments on the length of piles during nonlinear analysis are compared and the critical combination of soil around pile and behind the abutment was also identified. The maximum moment in pile head during the nonlinear analysis is shown in Table 5 for all nine cases, where it is clear that the maximum moment is always located at the pile-abutment connection. The maximum value of this maximum moment from all cases is 161.84 kN.m for case 3, with hard clay stiffness around the piles and loose sand backfill behind the abutments. The minimum value from all cases is 120.973 kN.m for case 4, with medium stiff clay around the piles and dense sand backfill behind the abutments. It is clear that moment along the pile is affected by the stiffness of the sand behind the abutment and adjacent to the piles in a different way from pile deflection. It is obvious that the maximum pile moment will decrease when the soil behind the abutment is compacted and increase when the piles are driven in stiff clay.

**Table.5 Time History Result in Critical Location**

| ID Case | pile head lateral force ( kN) | Pile head Displacement (cm) | pile head moment (kN.m) | girder axial force ( kN) |
|---|---|---|---|---|
| Hard Clay Dense Backfill | 45.719 | 0.7 | -146.95 | -25.621 |
| Hard Clay Medium Backfill | 44.9 | 1.75 | 158.25 | 93.1 |
| Hard Clay Loose Backfill | 98.049 | 1.53 | 161.84 | -103.86 |
| Medium Clay Dense Backfill | -16.404 | 1.75 .85 | 120.973 | 33.029 |
| Medium Clay Medium Backfill | 32.049 | 2.29 | 127.818 | -123.218 |
| Medium Clay Loose Backfill | -62.913 | 3.29 | 129.785 | -180.32 |
| Low Clay Dense Backfill | 98.049 | 1.57 | 130.524 | 116.75 |
| Low Clay Medium Backfill | 38.684 | 1.92 | 138.05 | 124.3 |
| Low Clay Loose Backfill | 23.115 | 1.71 | 130.78 | -180.32 |

As shown in Fig 13, 14 and 15, the highest degree of deflection happened at top of the pile during the time history analysis. The maximum deflection of nine cases of bridges along the piles is shown in diagrams. The peak value of these deflections from all nine cases is 3.35 cm for case 6 with medium stiffness clay around pile and loose sand behind the abutment and backwall, the minimum deflection is 0.7 cm with hard clay stiffness around piles and dens sand behind abutment and backwall. Thus it is obvious that lateral deflection of piles is affected by the soil stiffness around the piles and backside of the abutment. Pile lateral deflection will be reduced when the soil stiffness increases. In other words, when piles are located in stiff clay and backfilling is compacted, deflection is reduced. The maximum lateral displacement of abutment is usually located at bottom of the wall and adapted with pile lateral deflection.

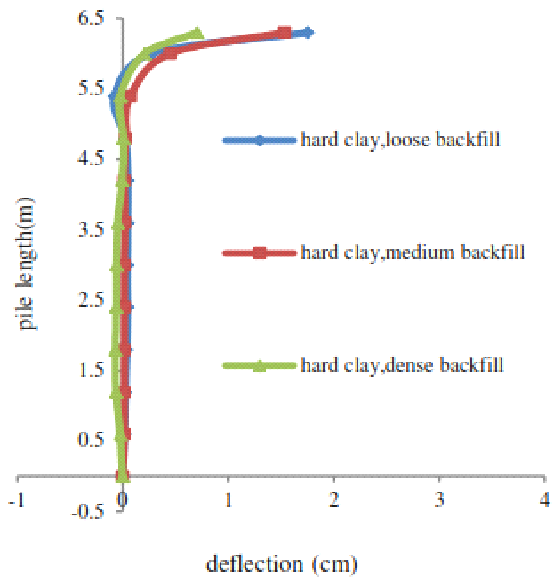


**Fig. 13: Lateral deflection of abutment case 1, 2, 3**

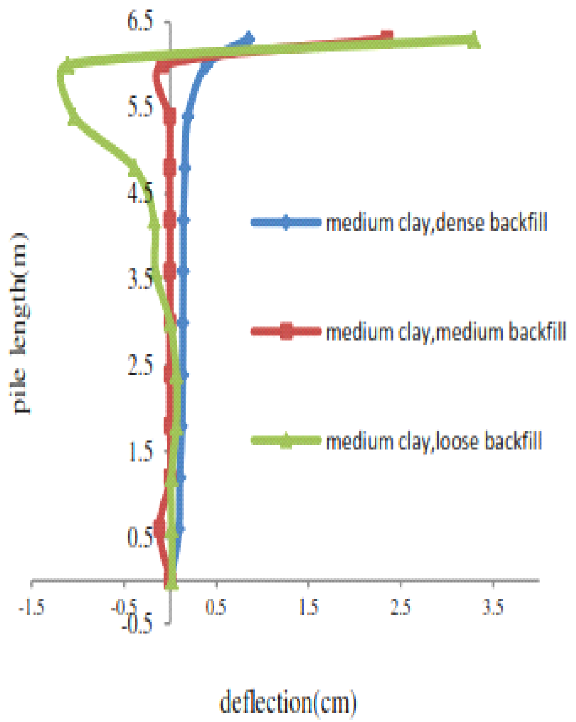


**Fig. 14: Lateral deflection of abutment case 4, 5, 6**

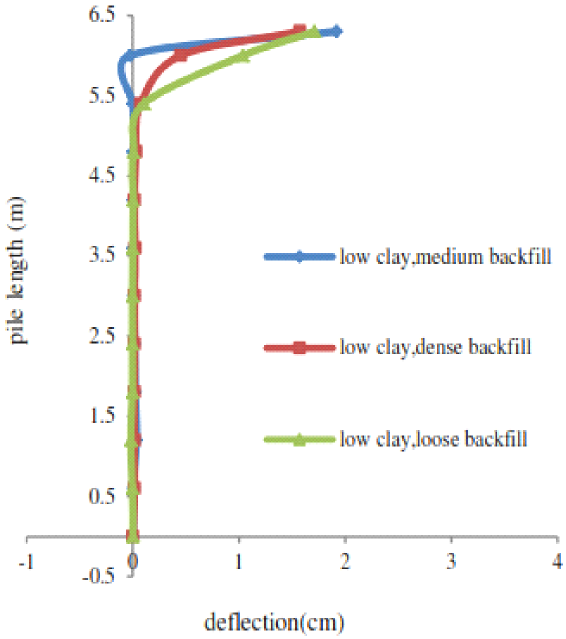


**Fig. 15: Lateral deflection of abutment case 7, 8, 9**

For the girder axial force, 180.32 kN the maximum values happen in case 6, with medium stiff clay around the piles and loose sand backfilling behind the backwall, while the minimum values happen in case 1 , with hard stiffness clay adjacent to the piles and dense sand backfilling behind the abutments wall. For the pile head lateral force at the abutments, the maximum value happens in case 3, with hard clay around the piles and loosely-compacted sand backfilling behind the abutments, while the minimum value happens in case 4, with medium clay around the piles and densely-compacted sand backfilling behind the abutments.

## VIII. CONCLUSION

Based on the time history analyses results, hard clay surrounding the pile increases pile head force, pile head moment and girder axial force that is a critical point in bridge design. For an integral abutment bridge that moves with soil around pile and behind the backfill, hard clay is not recommended for surrounding piles. Clay with low density that lets the structure move laterally and decrease force and moments in critical area is a better option. When seismic loading is applied on an integral abutment bridge in a longitudinal direction, maximum pile deflection and maximum abutment displacement happen at the pile head. These deflections are affected by the clay stiffness around the pile and in the backside of the abutment, and will decrease when the backfill is compacted or the piles are located in stiff clay, or both. Under seismic event, the maximum moment happens in the head pile. The pile head moment will decrease when the backfill is compacted and increase when the piles are located in stiff clay. herefore, this moment is maximum for the case with piles in hard clay and loose sand backfill, and minimum for the case with piles in medium clay and dense sand backfill. Dense sand in backfill behind the abutment wall is usually recommended, since it reduces the pile deflection, the abutment wall displacement, the girder axial force, and particularly, the pile moment.

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