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LEARNING OF SOIL BEHAVIOR FROM MEASURED RESPONSE OF A FULL SCALE TEST WALL IN SANDY SOIL

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ABSTRACT

In urban deep excavations, instruments are placed to monitor deformations and to control construction and reduce the risk of excessive and potentially damaging deformations. The second author has introduced a new inverse analysis approach that utilizes measured excavation performance to extract the underlying soil behavior. The extracted soil behavior can be used in predicting the behavior of similar excavations. This paper provides a first implementation of this inverse analysis approach to a well instrumented full scale test wall in a sand deposit. A wall consisting of soldier beams with wood lagging was instrumented to study anchored (one and two level tie backs) wall behavior in sandy soil deposits at Texas A&M. Strain gauges, load cells, inclinometers, and settlement points were placed in two sections of the excavation to monitor the excavation behavior. The measured excavation response for the section with two-level tie-backs is used to extract the constitutive model through the inverse analyses approach. The extracted constitutive model is used in predicting the underlying soil behavior for the section with one tie-back level. The predicted behavior of the excavation and its agreement with measurements at the site are discussed in detail.

INTRODUCTION

In urban areas there is a continuing and increased demand for underground space. Since the construction in this space could influence surrounding structures, observational programs are commonly set up at excavation sites to evaluate the design assumptions, determine causes of movements, improve the construction procedure, determine the need for immediate repair, and evaluate the stability of the excavation (Cording and Hansmire 1975).

Hashash et al. (2006), introduced a robust and efficient approach to extract soil behavior using SelfSim framework by integrating field observations and numerical modeling. SelfSim is an inverse analysis framework that implements and extends the autoprogressive algorithm proposed by Ghaboussi et al. (1998). It extracts behavior of materials facilitated by the use of a continuously evolving NN material model, rather than calibrating properties of conventional constitutive models. At a given excavation stage two complementary analyses are performed. First, the force boundary (construction sequence) condition is applied to extract stresses. Second, the measured field deformations (displacement boundary) are imposed on the model to extract strains. The extracted stress-strain pairs are used to re-train the NN material model until the two analyses give similar results.

The SelfSim analyses presented by Hashash et al. (2006) use lateral wall deflections and surface settlement measurements to capture excavation response and extract soil behavior. SelfSim framework is not limited to these two types of measurements and can benefit from other measurements. Marulanda (2005) studied the instrumentation layout for a few instruments and concluded that additional instrumentation can potentially be used to develop a more reliable extracted soil behavior. Song et al. (2007) extended the preliminary work by Marulanda (2005) to address: (a) which instruments contain key information on excavation soil behavior, (b) which instrumentation layouts improve the extracted soil behavior, and (c) which instruments provide redundancy for the purpose of soil behavior extraction. The study showed that after wall deformation and surface settlements, bracing forces have important information about the extracted soil behavior. In addition having inclinometers further away from the wall can improve the extracted soil material by capturing the small strain non-linearity in soil stiffness.

This study demonstrates the findings of Song et al. (2007), in which synthetic data was used, for a full scale model wall at Texas A&M. The wall, constructed in a sandy soil, was instrumented extensively to study the behavior of anchored walls. SelfSim is used to extract sandy soil behavior from excavation measurements supported by a two-level tieback section, and thereafter predict performance of one-level tieback supported excavation.

TEXAS A&M FULL SCALE MODEL WALL

The Texas A&M full scale model wall was constructed and tested as a part of research performed to improve the design of permanent ground anchor walls for highway applications (Weatherby et al. (1998)). A 7.5-m-high, instrumented, full-scale, tiedback, H-beam and wood lagging wall was constructed in an alluvial sand deposit to study various aspects of the behavior of anchored walls. Fig. 1 shows the location of the site at Texas A&M Riverside campus.

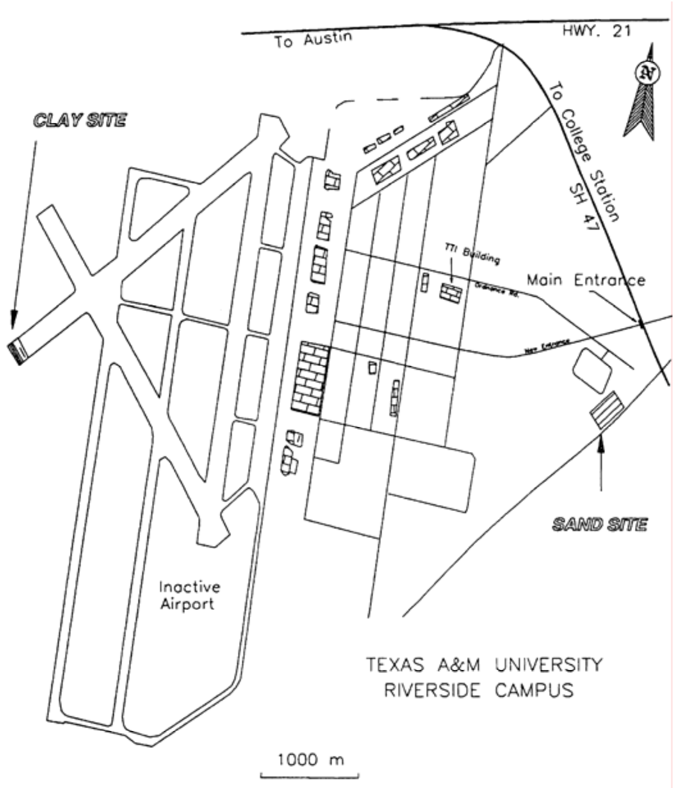
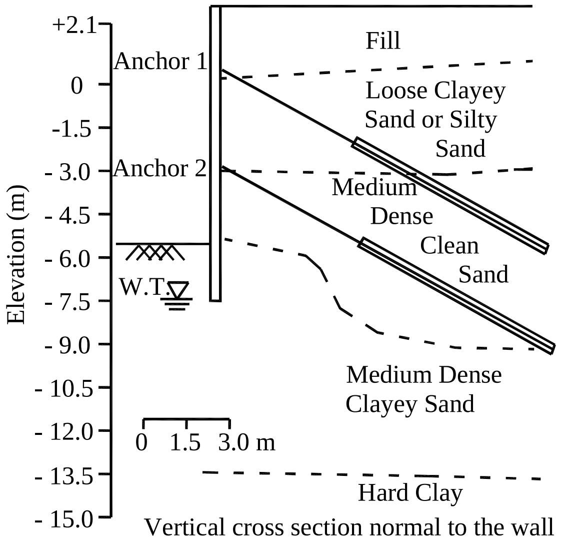
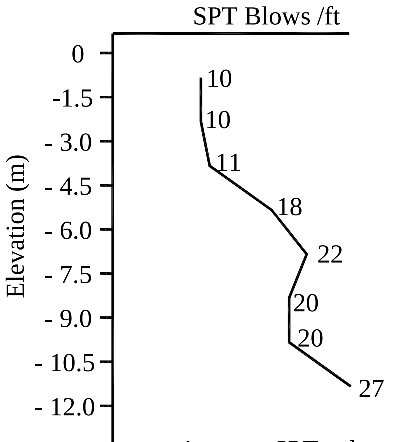


Fig. 1 Location of sandy site at Texas A&M University (Geotech. Special Publication No. 93)

A series of in situ tests were conducted to explore the soil profile at the site: three Standard Penetration Tests (SPT), three Cone Penetration Tests (CPT), three pressure-meters (PBPMT), one dilatometer test (DMT), and borehole shear test (BHST) (Weatherby et al. 1998, Benoit and Lutenegger 2000). The soil profile and average SPT values are shown *in Fig. 2.* The soil profile consists of fill overlying loose clayey sand followed by medium dense clean sand, and medium dense clayey sand. The fill is composed of silty and clayey sand, which was placed in 15- to 22- cm lifts and compacted with two passes of a fully loaded rubber tire pan scraper. The water table is 7.5 m below the ground surface. The friction angle was estimated to be between 30 to 32 degree using the correlation developed by Trofimenkov (1974) for loose clayey sand and medium dense sand layers at this site. The relative densities of the layers vary from 40 to 60 percent.



Vertical cross section normal to the wall



Average SPT values

Fig. 2 Soil profile and SPT results (FHWA-RD-98-066)

The wall which is supported by pressure-injected ground anchors has two sections. In Fig. 3, up to soldier beam number 12 the piles have lighter sections, (HP8x36, HP6x25), and therefore two level tiebacks are used in construction. For soldier beam numbers 13 to 22 one level tieback was used, because the piles have larger sizes, (HP10x57, HP12x53, HP10x42). Soldier beams 7 to 10 in the two-level tieback section and soldier beams 13 to 16 in the one-level tieback section are instrumented with inclinometers and surface settlement points, *Fig. 4.* Typical sections of the one level and two level tieback walls are shown in *Fig. 5*. *Table 1* summarizes the construction activities affecting the wall in the one and two-level tieback section of the wall. The excavation induced deformations measured at steps 2, 4, 5 and 7 for two-level tieback section and in steps 2, 3, and 6 for one-level tieback section of the wall.

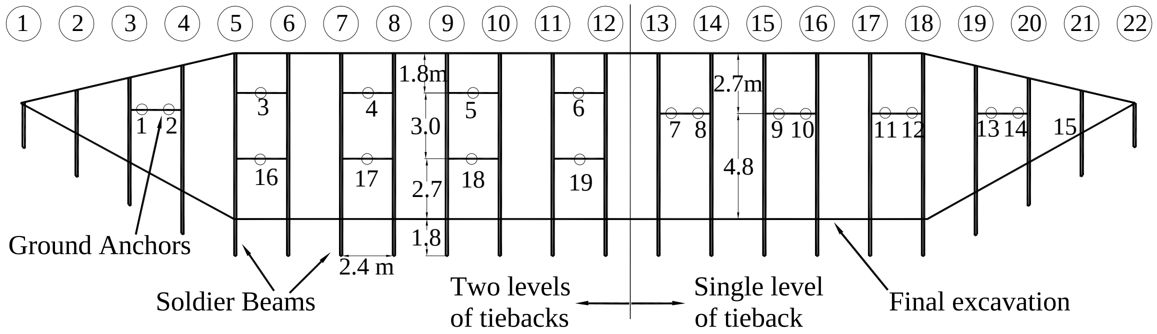


Fig. 3 Elevation view of the wall (modified after FHWA-RD-98-066)

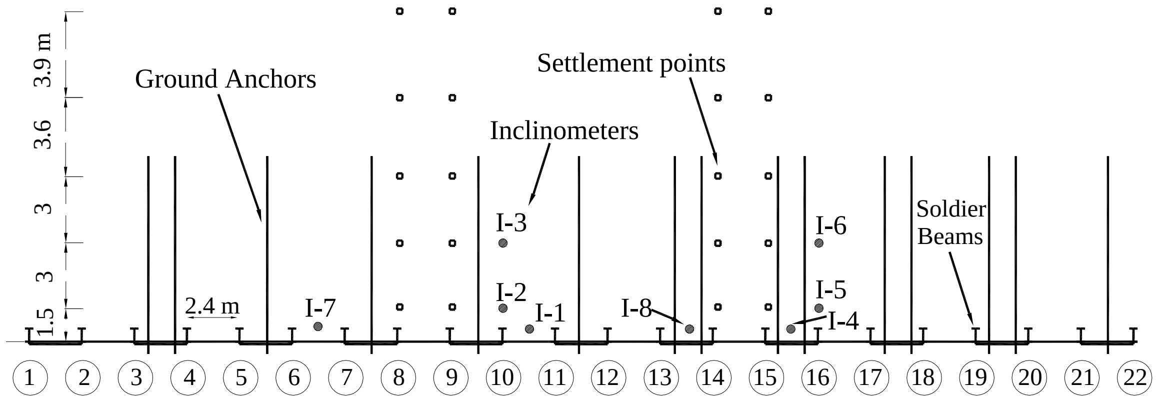


Fig. 4 Plan view of the wall (modified after FHWA-RD-98-066)

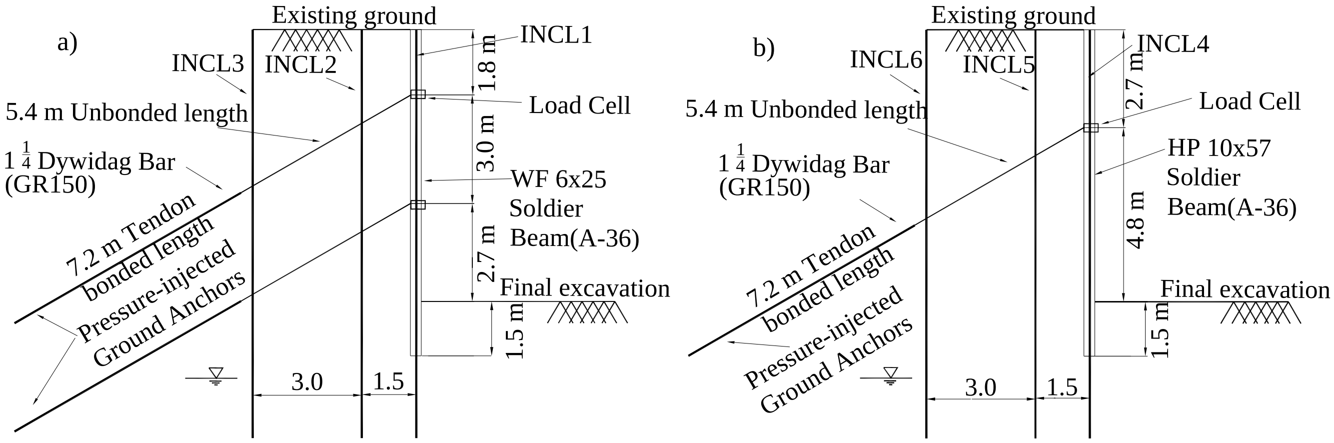


Fig. 5 Sections of the wall: a) Two level tieback, b) One level tieback (modified after FHWA-RD-98-066)

Table 1. Wall construction activity and measurement dates

	Two-level tieback section		One-level tieback section	
	Activity	Measurement	Activity	Measurement
Step 1	1.2m excavation		1.2m excavation	
Step 2	2.4m ft excavation	86th day	3m excavation	96th day
Step 3	Upper tieback installation		Tieback installation	101st day
Step 4	5.1m excavation	108th day	4.2m excavation	
Step 5	Lower tieback installation	114th day	6.3m excavation	
Step 6	6.3m excavation		7.5m excavation	122nd day
Step 7	7.5m excavation	122nd day		

MODEL USED IN SELFSIM

The full scale model wall is simulated using solid element with a bending stiffness equivalent to that of the soldier-pile wall. The tiebacks are simulated by elastic spring elements. The soil profile in the analyses consists of four representative layers for fill, loose clayey sand, medium dense clean sand and medium dense clayey sand. The construction sequence used in the analyses is shown in *Table 1*. The inverse analysis is conducted using SelfSim (Hashash et al. 2004, Hashash et al. 2006) whereby the measured response from instruments is learned while the underlying soil behavior is extracted.

LEARNING SOIL BEHAVIOR FROM TWO-LEVEL TIEBACK SECTION OF THE WALL

Learning soil behavior using wall deformations (I-1) only

Fig. 6 shows the results of forward analysis after SelfSim learning from wall deflection measurements only. The computed response of the wall is reasonably matched with the measurement values, but the lateral movements at I2 or I3 and vertical movements of settlement points are not predicted well. In the last stage of full scale model wall construction (i.e. 122nd day), the soldier beam piles settled/slipped. The measured subsurface settlement behind the wall reflects the same observation (i.e. the slippage of the wall induced large settlements behind the wall). *Fig. 6* shows that the predicted movements at location of inclinometer 2 (I-2) reasonably matches the measured values up to stage 5, but in the last stage of excavation the predicted movements underestimate actual measurements. This effect is not observed at inclinometer 3 (I-3) as I-3 is further away from the wall (4.5 m from the wall) and is less affected by the settlement of soldier beam piles.

Learning soil behavior using wall deformations (I-1) and inclinometer measurements at I-3

SelfSim learning is conducted using wall deformations (I-1) and lateral deflections of the inclinometer 3 (I-3) in order to improve the extracted soil behavior. *Fig. 7* shows the computed excavation response. Comparison of *Fig. 6* and *Fig. 7*, illustrates that not only the wall deflections are extracted reasonably, but also the lateral deformations of inclinometer 3 better matched the measured values.

Learning soil behavior using wall deformations (I-1), inclinometer at I-3 and tieback loads

Final SelfSim learning analysis is conducted using the lateral deformations of the wall and inclinometer 3, and tieback loads to capture the change in lateral deformations of the wall after tieback installation. *Fig. 8* shows the computed excavation response. The lateral movements of the wall and inclinometer 3 are improved compared to the results in *Fig. 6* and *Fig. 7*.

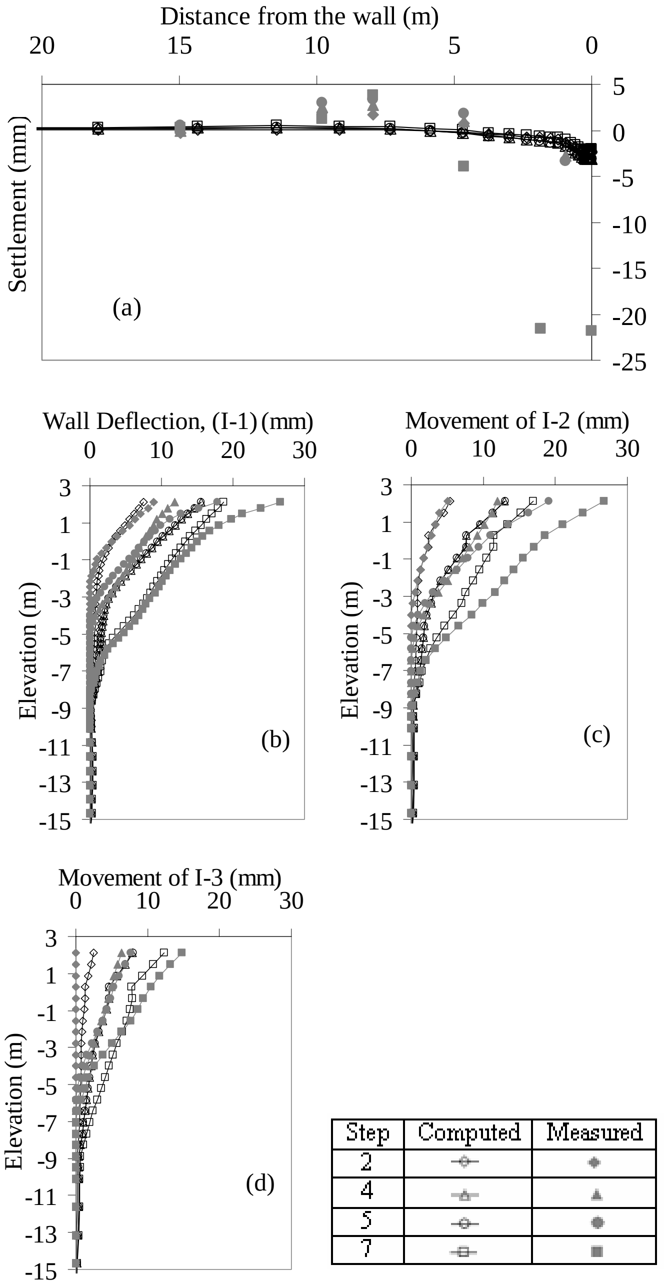


Fig. 6 Computed response after SelfSim learning with wall deformations only; a) surface settlements, b) wall deflections, c) lateral movements at inclinometer 2, and d) lateral movement at inclinometer 3.

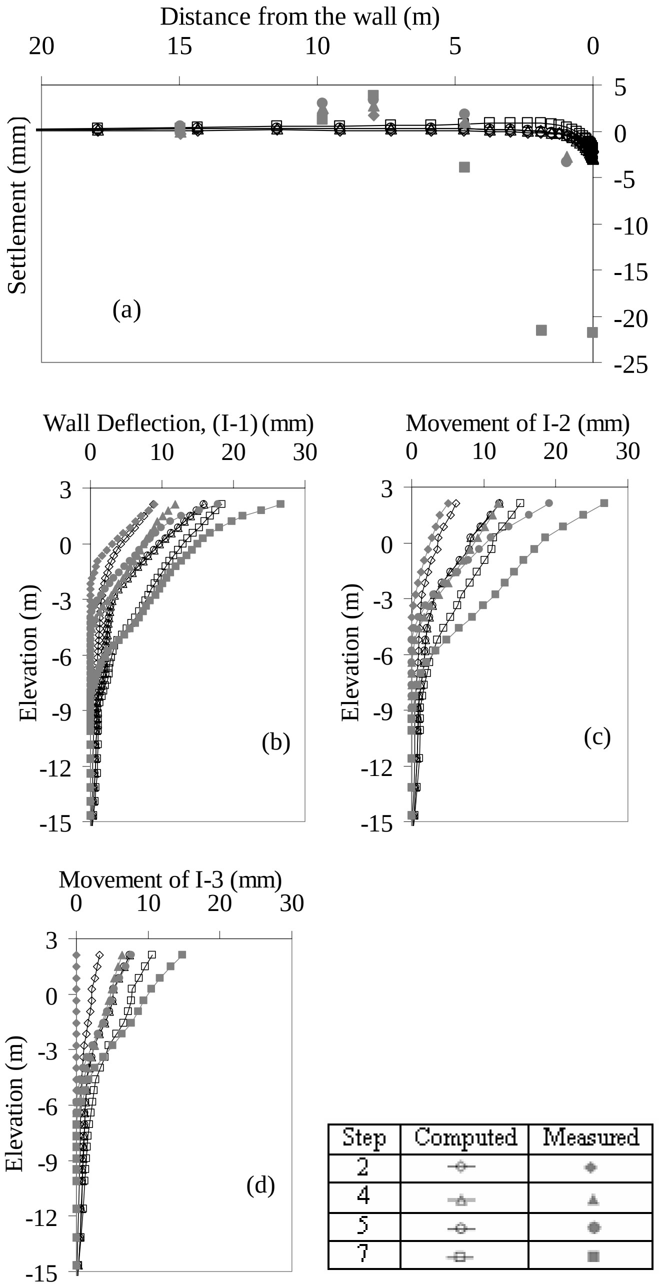


Fig. 7 Computed response after SelfSim learning with wall deformations and inclinometer 3; a) surface settlements, b) wall deflections, c) lateral movements at inclinometer 2, and d) lateral movement at inclinometer 3.

Fig. 9 shows the comparison of measured and computed tieback loads. The computed tieback loads after learning with wall deflection (I-1), lateral movement at inclinometer 3 (I-3) and tieback loads are reasonably matched with the measured loads. When only wall deformations or wall deformations and lateral deformations at inclinometer 3 are used in SelfSim learning, the computed tieback loads are overestimated.

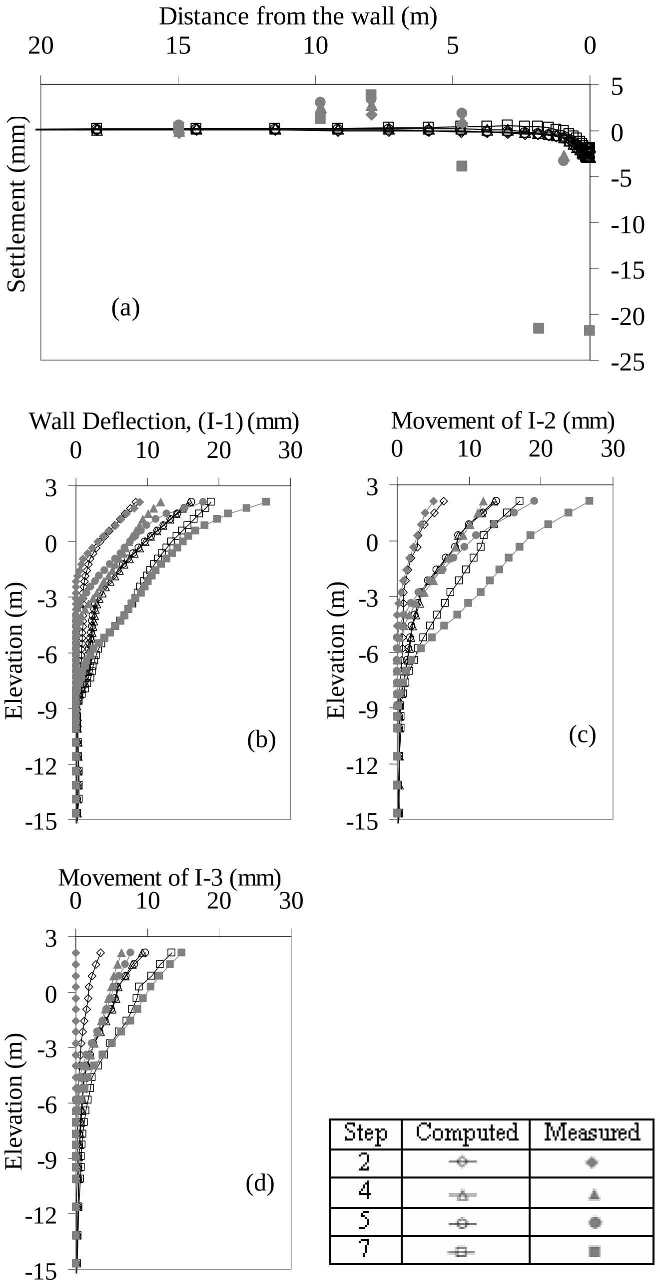


Fig. 8 Computed response after SelfSim learning with wall deformations, inclinometer 3 and tieback loads; a) surface settlements, b) wall deflections, c) lateral movements at inclinometer 2, and d) lateral movement at inclinometer 3.

PREDICTION OF EXCAVATION BEHAVIOR IN ONE-LEVEL TIEBACK SECTION OF THE WALL

The developed model from SelfSim learning with wall deflections, lateral movements at inclinometer 3 and tieback loads of two-level tieback section is used to predict the soil behavior in one-level tieback section of the wall. The wall height is the same as the two-level tieback wall section (*Fig. 5*), but larger sections of the soldier beams are used for wall construction. *Table 1* shows the corresponding construction sequence.

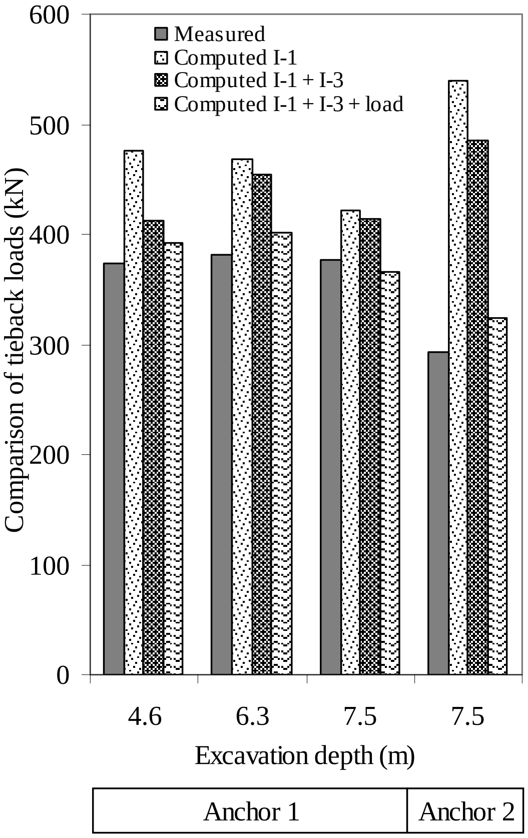


Fig. 9 Comparison of measured and computed tieback loads of tiebacks after SelfSim learning with wall deflection (I1), lateral movement of I3 with and without tieback loads in two-level tieback section of the wall

Fig. 10 shows the predicted excavation behavior. Since heavier soldier beams are used in one-level tieback section, the deformations are generally less than the two-level tieback section. The predicted deformations in *Fig. 10* show that the extracted soil behavior from two-level tieback section of the wall, used in a numerical analysis, predicts reasonably the lateral movements of inclinometers in one-level tieback section.

Fig. 11 shows compares predicted and measured tieback loads in one-level tieback section of the wall. The predicted loads are reasonably predicted for two out the three construction stages.

CONCLUSIONS

This paper presented a case study to employ field instrumentation to capture sandy soil behavior in an excavation at Texas A&M. The soil behavior in two-level tieback section of the wall has been extracted using inclinometer measurements and tieback loads through the SelfSim inverse analysis framework.

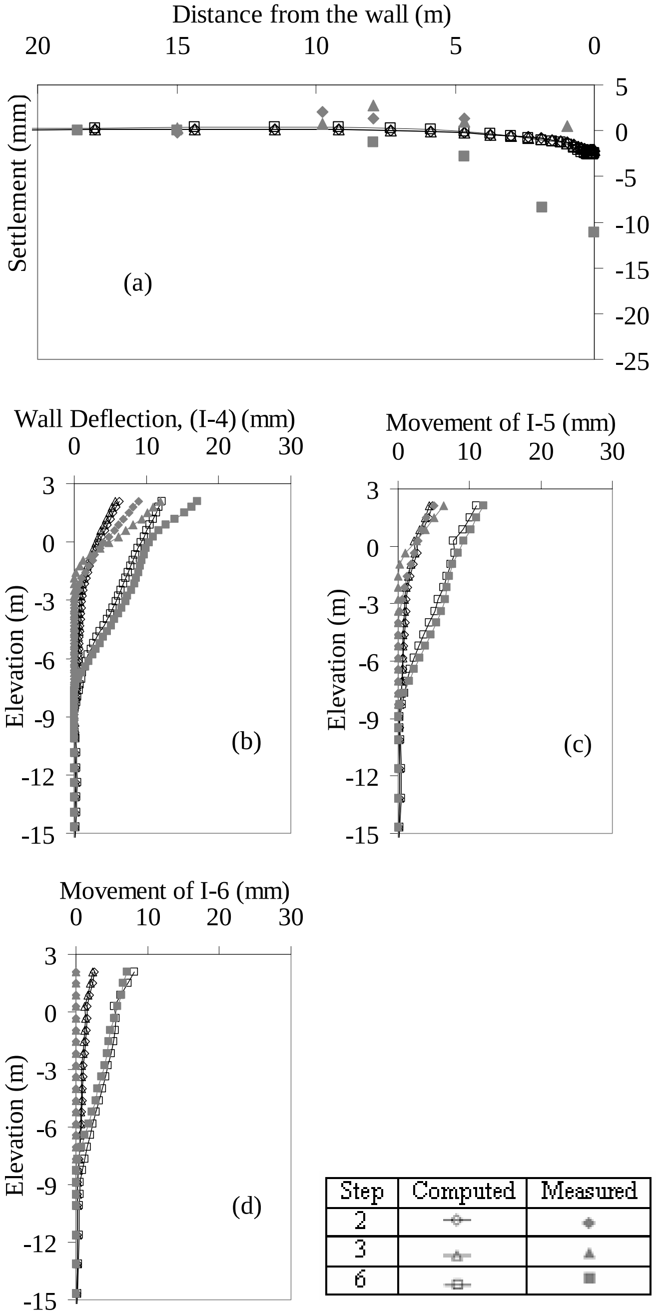


Fig. 10 Predicted excavation response in one-level tieback section of the wall; a) surface settlements, b) wall deflections, c) lateral movements at inclinometer 2, and d) lateral movement at inclinometer 3.

The extracted soil behavior from the two-level tieback section of the wall was used to predict the excavation behavior in one-level tieback section of the wall. This study shows that:

1. Wall deformations are essential information for learning of overall excavation behavior; however they are not enough to capture the global behavior.
2. Additional inclinometers placed farther back from the wall provide supplementary information that can be

used to complement prediction of excavation behavior

3. Bracing loads provide valuable information to extract soil behavior.
4. The extracted soil behavior from two-level tieback section of the wall could predict reasonably well the excavation behavior in one-level tieback section of the wall.

Ongoing research is focusing on understanding the extracted soil behavior and its relation to known soil properties at the site.

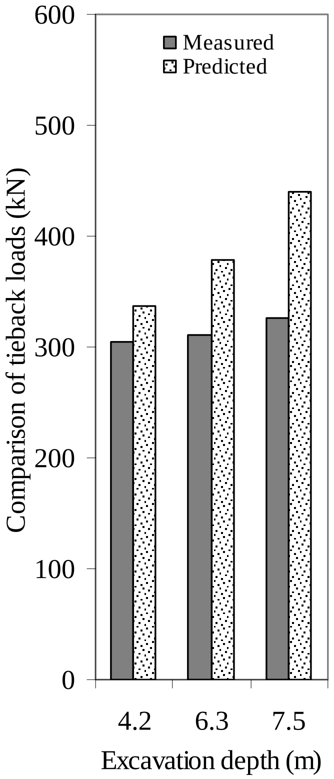


Fig. 11 Comparison of measured and predicted load of tiebacks in one-level tieback section

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