

Seismic displacements of retaining walls: shaking table test results vs numerical predictions

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Abstract – The seismic performance of retaining walls is usually evaluated through simplified displacement-based approaches which neglect the change in the soil-wall system geometry as displacements develop. In this vein, the paper describes the results of several shaking table tests carried out on a reduced-scale model of a retaining wall placed inside a flexible soil container and subjected to harmonic input motions. In the paper the permanent displacements of the wall and of the retained soil were presented and compared with numerical predictions obtained using a modified Newmark-type model, which encompasses the kinematic compatibility between the wall and the soil.

I. INTRODUCTION

The seismic response of retaining wall represents a complex soil-structure interaction problem, which involves ground motion modification and cyclic plastic deformations in the retained soil possibly leading to large permanent displacements and/or rotations of the wall. Accordingly, the seismic performance is usually predicted using simplified displacement-based approaches derived from the original Newmark's sliding block method. In this context the effect of the change in the soil-wall geometry, as displacements develop, requires further understanding. In this vein, the paper summarizes the results of several shaking table tests carried out using a scaled concrete retaining wall placed inside a flexible container filled with Leighton Buzzard sand. Experimental values of the permanent displacements of the wall and of the retained soil were used to check the capability of a modified Newmark-type model which accounts for the kinematic compatibility between the wall and the retained soil as displacements develop.

II. EXPERIMENTAL SETUP AND TEST RESULTS

The experimental activities were performed at the old Earthquake Engineering Research Centre of Bristol University [1] using the large (3x3m) shaking table (only 1 degrees of freedom was activated during the tests), the small shear stack (119 x 81.4 x 55 cm) and a concrete wall model (height 50 cm, weight 1.3 kN) designed, on purpose, to slide along the base with negligible tilting

effects even in cases of large accelerations. Figure 1 show a comprehensive scheme of the experimental setup.

The shear stack was fixed to the shaking table and, once the wall model has been placed, was filled with Leighton Buzzard Sand using a special deposition procedure which leads to a soil relative density in the range 55-70%. To realize a smooth interface the back face of the wall model, and the internal side of the lateral walls of the shear stack, were greased and covered with a thin latex membrane. Conversely, to create a rough surface, a thin layer of sand was glued to the bottom of the shear stack and to the internal side of the end walls of the shear stack. In some tests a thin (5 mm) layer of sand was adopted to modify the friction at the wall base.

Horizontal and vertical acceleration and displacement responses of the wall were monitored using 4 Setra piezometric unidirectional accelerometers (*S13*,...,*S16*) and 6 Celesco displacement transducers (*C6*,...,*C11*). The response of the retained soil was recorded using 9 Setra piezometric unidirectional accelerometers and 2 Indikon no-contact magnetic transducers: the accelerometers (*S4*,...,*S12*) were installed inside small boxes (to which a thin layer of sand was glued) placed inside the sand deposit (at different depths) along two alignments selected according to the static and seismic active wedge geometry; the no-contact transducers (*I2*, *I3*) were placed at the soil free surface to record the vertical displacement of the active soil wedge (*I3*) involved in the seismic failure mechanism.

Complementary tests (white noise excitation tests and various friction tests) were also performed to estimate the mechanical properties of the system and the friction available at the base of the wall model. An average value $\phi_b \approx 30^\circ$ of the friction angle along the wall base was estimated with an average variability of about $\pm 1^\circ \div 3^\circ$.

Further details on the instrumentation, on the soil mechanical properties and on the soil deposition procedure can be found in [2] and [3].

During the shaking table tests, several sine-dwell displacement time-histories were applied increasing the amplitude run by run. Each run was characterized by 30 cycles and a constant frequency f equal to 3 (test 3,5), 5 (test 2,6) or 7 Hz (test 4,7).

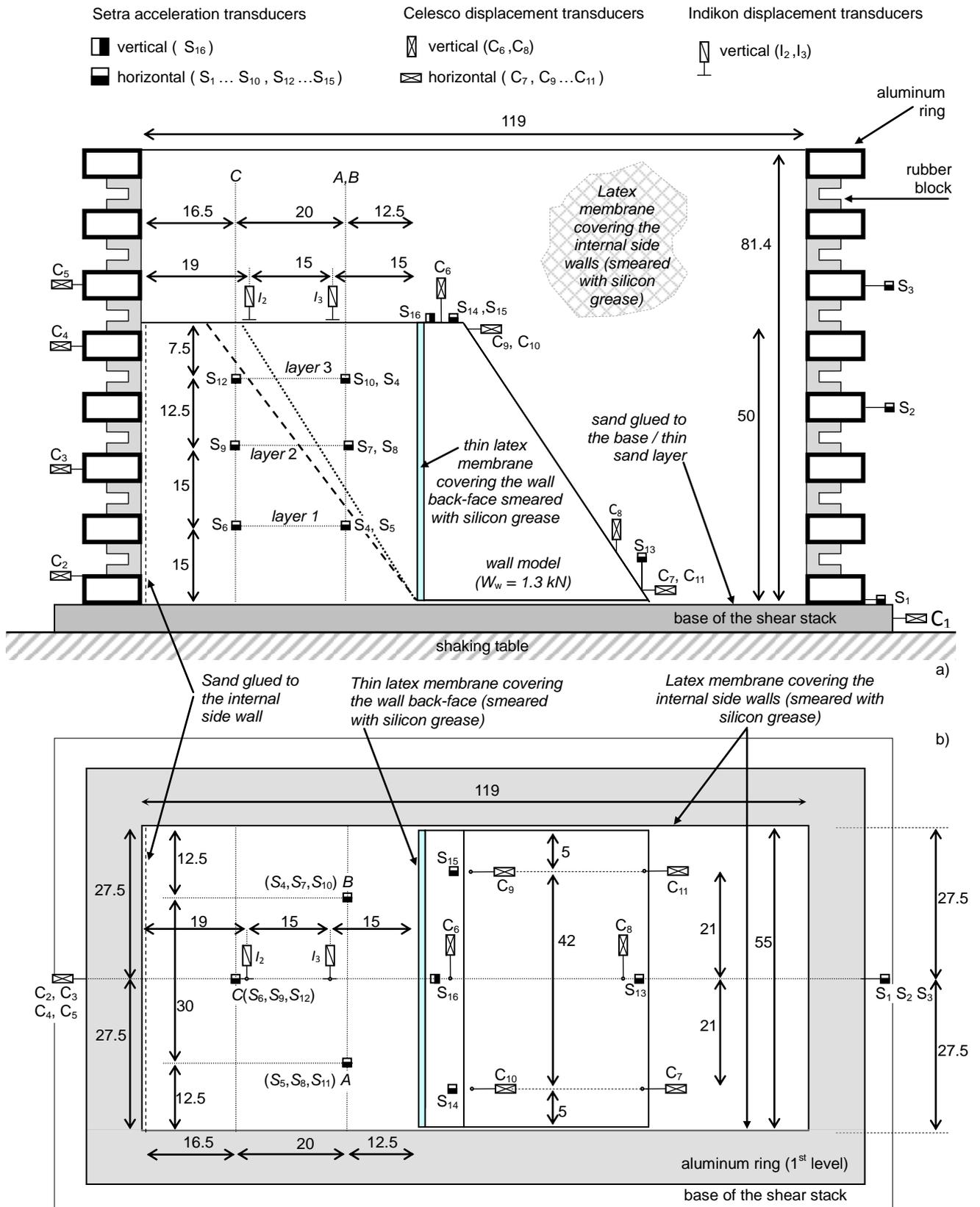


Fig. 1. Schematic of the experimental setup.

The amplitude of the input motion increased in the first 5 cycles, reduced to zero in the last 5 cycles, being constant in intermediate 20 cycles.

[1] provides a comprehensive description of all the test results. A summary of the shaking table test results is presented in Figure 2 and 3. Figure 2 shows the plots of the wall permanent displacements ($d_{max,w}$) and peak horizontal acceleration ($a_{max,w}$) versus the displacement ($d_{max,T}$) and acceleration ($a_{max,T}$) amplitudes imposed to the table. Threshold values of $d_{max,T}$ and $a_{max,T}$, below

which no significant displacements of the wall occurred, can be easily detected being significantly influenced by the input frequency f . Figure 3 shows the profile of the soil free surface detected at the *end* of the last run of each tests. In the figure the *initial* (undeformed) configuration of the soil-wall system is also represented for comparison together with the static and seismic active wedges, the latter computed for the greater values of the peak horizontal acceleration $k_{h,max}$ recorded in the soil.

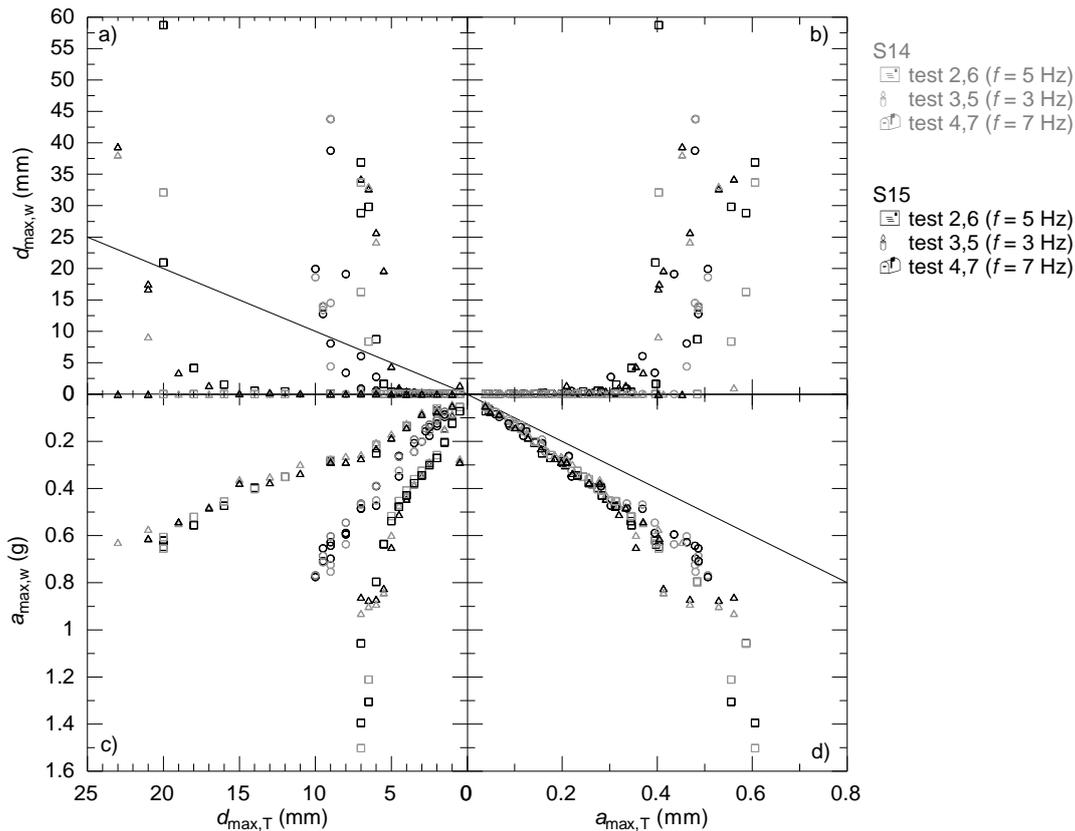


Fig. 2. Wall permanent displacements ($d_{max,w}$) and wall peak acceleration ($a_{max,w}$) versus input displacement ($d_{max,T}$) and acceleration ($a_{max,T}$) amplitudes (after [1]; modified).

III. THEORETICAL ANALYSIS

A displacement analysis is often used to evaluate the seismic performance of rigid retaining walls [4-6]. A modified Newmark-type model was recently proposed by [7] which generalized a two-wedge approach originally developed by [8] and [9]. The reference scheme for the analysis, together with some relevant formulas, is shown in figure 4a. Figure 4b shows the plots of the pseudo-static safety factor of the wall, against sliding (SF_s) or tilting (SF_t), computed for an angle of soil shear strength $\phi' = 35^\circ$ ([1]), assuming an horizontal active thrust ($\delta = 0$), a normalized wall weight $\Gamma_w = 0.62$ and $\phi_b \approx 30^\circ$. As it was anticipated, the seismic response of the wall

should be characterized by a sliding failure mechanism whatever is the input accelerations.

The model introduces a shape factor S_F to describe the condition of kinematic compatibility, between the wall and the retained soil, which requires the same magnitude for the components of the displacement vectors d_w (of the wall) and d_s (of the soil wedge) normal to the boundary between the two wedges. Figure 4c shows the values of S_F computed, for the wall model considered herein ($i = \beta = 0$, $\delta/\phi' = 0$, $\Gamma_w = 0.62$), assuming different values of ϕ' and of the friction angle ϕ_b .

According to [5] two displacement factors, C_w (for the wall) and C_s (for the soil wedge), can be introduced in the displacement analysis and the corresponding permanent

displacements, d_w and d_s , can be computed starting from the displacement d_o of a rigid block sliding, along a horizontal plane, with the same yield acceleration $k_{h,c}$ of the actual soil-wall system. Figure 2d shows the values of

C_w and C_s for the same case considered in Figure 2c. For the soil-wall system considered herein it is $S_F = 0.51$, $C_w = 0.73$ and $C_s = 1.43$.

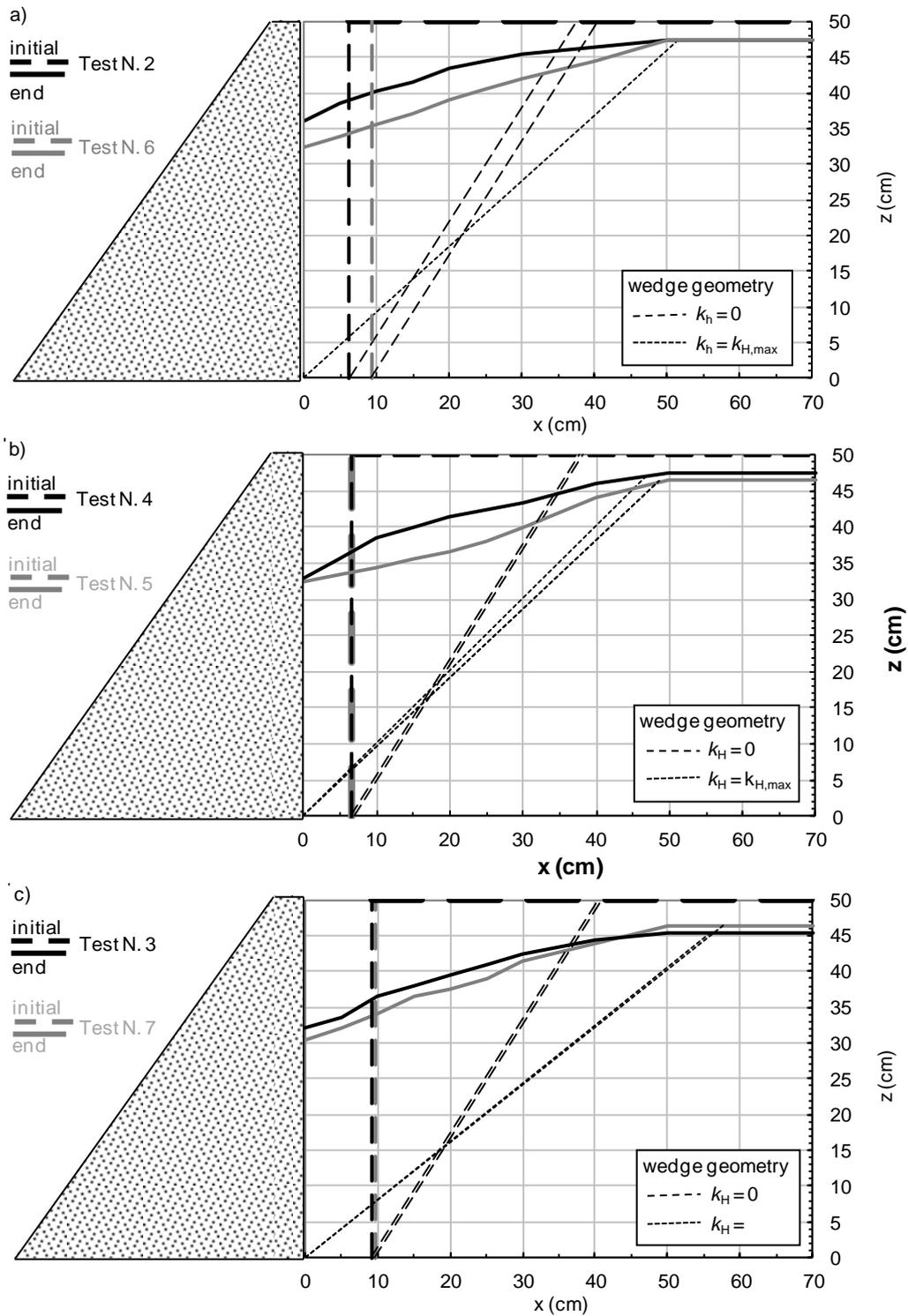


Fig. 3. Initial (undeformed) and final (end of test) configurations of the soil-wall systems and soil wedge geometry.

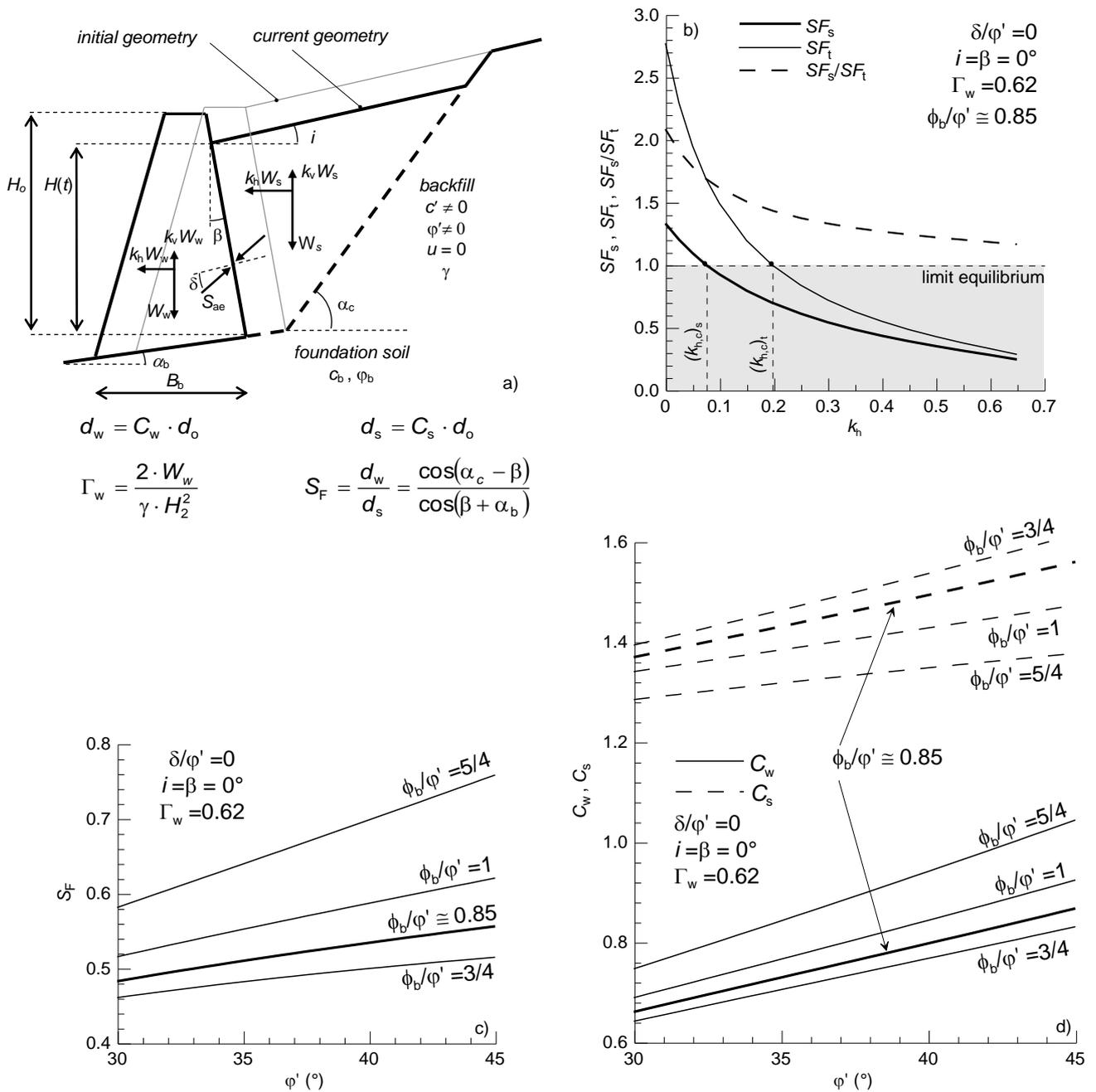


Fig. 4. a) theoretical soil-wall system (after [7], [8], [9]; modified); b) pseudo-static safety factors; c) wall (C_w) and soil (C_s) displacement factors; d) shape factor S_F .

IV. DISCUSSION AND CONCLUSIONS

Some of the experimental results previously described were examined to check the capability of the considered theoretical model.

To this purpose, the configurations of the soil-wall system detected at the end of the tests (Fig.3) were adopted to compute several values of the shape factor directly from the measured permanent displacements.

Since the soil wedge did not behave as a rigid body, two reference values of its permanent displacements, $d_{s,o}$ and $d_{s,1}$, were detected referring to the upper point of the wall-wedge interface (Fig. 5a). Accordingly, for each tests two values of S_F were estimated as the ratio between the horizontal permanent displacement of the wall (d_w) to the component d_s of $d_{s,o}$ or of $d_{s,1}$ along the sliding surface (inclined of α_c to the horizontal - Fig. 5a).

The comparison between 'measured' and theoretical values of S_F is presented in Figure 5 b,c.

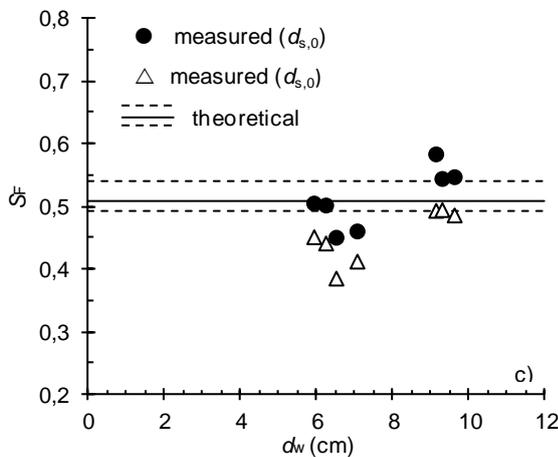
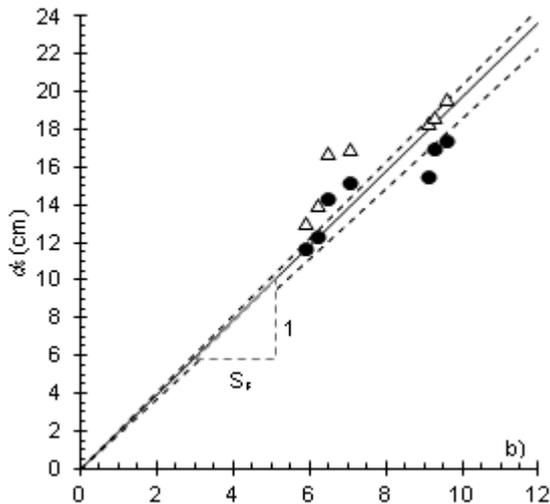
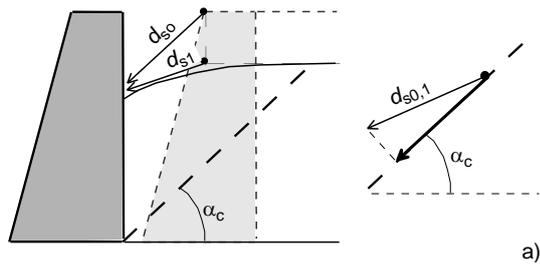


Fig. 5. Comparison between measured and theoretical values of displacement ratio.

Specifically, measured values of d_s are plotted versus the corresponding values of d_w in Figure 5b where the theoretical solution corresponds to the continuous line whose inclination is equal to $1/S_F$ (with S_F estimated assuming an average values $\phi_b \approx 30^\circ$ of the friction angle at the wall base); in Figure 5c the comparison is presented in terms of values of S_F . The two dashed lines in Figure 5b,c represent the theoretical solutions obtained using the minimum and the maximum values of the

friction angle obtained in the friction tests.

As it can be observed a fair agreement exists between the values of S_F computed from the experimental results and those obtained through the theoretical approach. The match of the two sets of data is satisfactorily in all the considered cases regardless the frequency and the amplitude of the displacement time-histories adopted as input motion during the test. The capability of the model is, thus, verified.

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