Assessment of strut load redistribution due to removal of individual strut of an excavation support

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ABSTRACT: It is a common practice that deep excavation retention system is analysed using a two-dimensional finite element analysis. Design of strutting system should consider sequential removal of struts as part of the construction staging known as one-strut failure (OSF) case. Analysing the removal of struts with a two dimensional finite element model (in plane strain) has limitations due to three dimensional nature of the problem.

A comparison study was undertaken using Plaxis2D and Plaxis3D to assess the re-distribution of loads to the adjacent struts when an individual strut within the retention system is removed assuming that the loads on all other structural elements are within their capacities. A multi-level strutted piled wall was analysed by removing one strut at a time from each level and assess how the load was redistributed to the adjacent struts.

Strut removal is simulated by adjusting the stiffness of each of the multi-level struts. By undertaking this comparison study, it is possible to justify the assumption made for the two-dimensional analysis. The comparison results of the 2D and 3D numerical analyses are presented and discussed in this paper.

1 INTRODUCTION

Over the last few years geotechnical and structural engineers rely heavily on the use of numerical methods to predict the behavior and performance of deep excavation retention system. This is contributed mainly by the availability of user-friendly finite element (FE) and finite difference (FD) software packages.

CIRIA Report C580 (2003) provides guidance on the use of numerical methods for excavation and lateral support for both serviceability limit state (SLS) and ultimate limit state (ULS) calculations. This Report has been revised and superseded by CIRIA Report C760 (2017).

In Australia, most practicing geotechnical engineers refer to AS5100.3 (Standards Australia, 2017) when undertaking design of excavation retention systems. This standard provides commentaries and guidance on the load combinations for strength and stability design of soil-supporting structures.

Strutting is often chosen as the preferred propping system to provide supports along the perimeter of an excavation retention system for both permanent and temporary works.

It is common that 2D plane strain FE analysis is often used to analyse an excavation retention system due to simpler modelling and lesser computing time compared to 3D analysis.

For temporary works, design of strutting system should consider those cases where struts at each level within the retention system are required to be progressively removed as part of the construction staging. This is commonly known as one-strut failure (OSF) case (TR26, 2010). Solving OSF with two dimensional soil-structure analysis has limitations due to three dimensional nature of the problem

In this paper, the authors carry out a comparison study of both 2D and 3D numerical analyses to assess the re-distribution of loads to the adjacent struts when an individual strut within the retention system is removed. A comparison study was undertaken using Plaxis2D and Plaxis3D

2 STRUTTING MECHANISM

2.1 *Soil Arching*

In strutted excavation, arching soil movement occurs in two ways. In the lateral direction, soil movements at the strut locations are restrained while the remaining soils flow around the struts and develop the arch. In the vertical direction, the soil is restrained from moving at the wall supports (i.e. strut and waler positions), the inside corners and bottom edges of an excavation while the remaining soils flow around the wall support and again develop the arch.

This soil arching effect causes the complexity of soil pressures behind a strutted wall system, which are different from a triangular stress distribution that is usually calculated using the Rankine or Coulomb method (Turner, 2009). This effect can be modelled and explained better using numerical methods. However, difficulties are still present if the problems are complex such as three-dimensional OSF cases.

2.2 *Stiffness of struts*

In two-dimensional plane strain analysis, stiffness of struts is commonly calculated as an equivalent stiffness assuming both struts and waler beams are modelled as two springs in series as shown in Figure 1 (Pong et. al., 2012).

The equivalent stiffness is expressed in Equation 1 below.

$$\frac{1}{K_{eq}} = \frac{1}{K_w} + \frac{1}{K_s} \qquad (1)$$

where K_{eq}, K_w and K_s are equivalent, waler beam and strut stiffness, respectively.

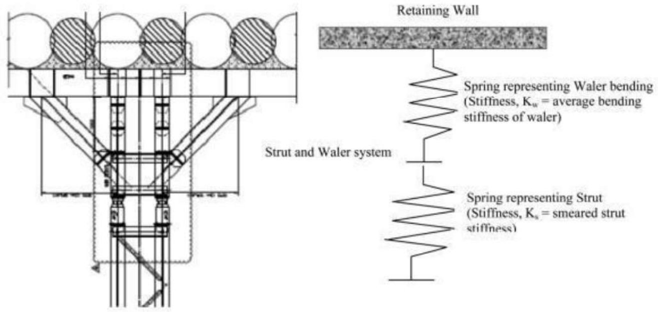

Figure 1. Strut-waler beam idealisation (after Pong et. al., 2012)

Under a normal case, K_w can be omitted due to short spans of the waler beams and therefore, K_{eq} is taken as K_s. This means that soil pressures behind the wall is partly transferred to the struts through waler beams.

2.3 *Approximate strut stiffness in OFS*

In a OSF case, a single strut is removed and its implication is a reduction in stiffness of the overall strut system. There is no complexity in the 3D analysis as any struts can be conveniently removed from the 3D model. However, it is difficult to analyse such a case in a 2D model as the effect of removal of a strut on the strut stiffness cannot be easily quantified for estimating the additional loads distributed to adjacent struts.

Conservatively in the 2D analysis, OSF is usually modelled by removing the strut layer. This approach does not consider the contribution of the remaining struts in the same layer as the removed strut.

Another better approach is to include the waler beam stiffness at the level of the removed strut. The span of the waler beam now becomes larger than the initial span i.e. spacing between struts prior to strut removal. To model this approach, the stiffness of the layer of removed strut needs to be reduced due to the span increase of the waler beam.

The above approach is discussed below. Figure 2 shows a typical plan view showing the removed strut, adjacent struts and a continuous waler beam. The lateral spacing between struts is *s* and strut length is *L*. It is also assumed that when one strut is removed, there is an effective length of the waler beam that could replace the stiffness of the remaining struts and a uniformly distributed load acting on the waler beam (*q*). Such an effective length of the waler beam is defined with a constant parameter, *m*.

The strutwaler beam system is to satisfy both force equilibrium and displacement compatibility criteria.

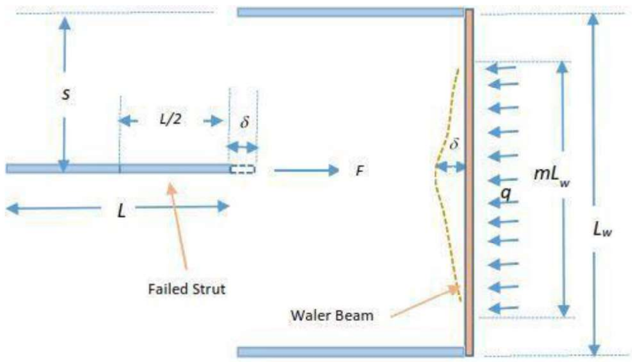

Figure 2. Plan view of strut-waler beam at a certain depth.

The displacement of strut can be calculated using the 1D Hooke's equation (equation 2).

$$= \frac{F(L/2)}{E_s A_s} \qquad (2)$$

Where F, E_s and A_s are axial force in the strut, the elastic modulus and cross-sectional area of the strut, respectively.

The displacement of the waler beam with a span of L_w (= 2*s* after removal of one strut) can be expressed using equation 3 which is based on the maximum deflection of the simply supported beam under uniform load with parameter *m* in the beam length to define an effective length of the waler beam.

$$= \frac{1}{384 E_w I_w} q \left(mL_w \right)^4 \qquad (3)$$

Parameter *m* is a function of the distribution of loads from the removed strut to the adjacent struts, both within the same layer and the ones above and below the removed strut. E_w is elastic modulus of the waler beam and I_w is inertia moment of the waler beam.

By substituting equations 2 and 3, the stiffness of the layer of strut, from which one strut has been removed, can be approximated using equation 4 below.

$$E_sA_s = \frac{E_w I_w L}{192\,(mL_w)^3} \tag{4}$$

3 ASSUMPTION FOR OSF ANALYSIS

Many temporary deep excavation projects involve multi-level strutting system installed at different construction stages. The OSF cases in this paper focus only on a particular row of struts of the 3D model (refer Figure 3). 2nd row struts are the struts installed within the same vertical plane where the removed strut is located.

The following assumptions are considered in the present study:

- Similar lateral strut spacing for all layers in the 3D model.
- Critical condition for each OSF case (for a particular layer of struts) occurs when excavation reached the bottom of the next excavation level but before the commencement of installation of struts for this level. For example, OSF occurs at Strut S3 when excavation reached S4 level but before the commencement of installation of Strut S4.

4 METHODOLOGY

4.1 *Case study*

A hypothetical case chosen for the present study was a deep excavation project. For this study, geometry, strut properties and ground profile and properties had been simplified. It was also assumed that no build-up of the groundwater pressure behind the wall during construction.

The retention system comprised embedded 1200 mm diameter bored piles spaced at 1.9 m center-to-center and a strutting system consisting of a temporary deck and six levels of struts (S1, the topmost strut layer to S6, the lowest strut layer). Each actual pair of close struts was modelled as a single strut in the 2D model. Struts were nominally analysed at 7.7 m horizontal spacing for all strut layers. The bottom of excavation was 40 m below the ground level.

The excavation site was surrounded by existing buildings and surcharge loads between 30 kPa and 60 kPa were applied behind each side of the walls to represent the building loading.

The excavation model and associated structures are shown in the Plaxis 3D model in Figure 3.

4.2 *Geotechnical model*

The geology, assumed for the analyses, stratigraphically comprised fill overlying residual soils which were underlain with interbedded metasedimentary rocks. The metasedimentary rocks for the present study was then sub-divided into three classes based on weathering and strengths (MS3 is the lowest strength and heavily weathered to MS1 the highest strength and slightly weathered). Table 1 summarises the stratigraphy sequence and depths of each geotechnical unit.

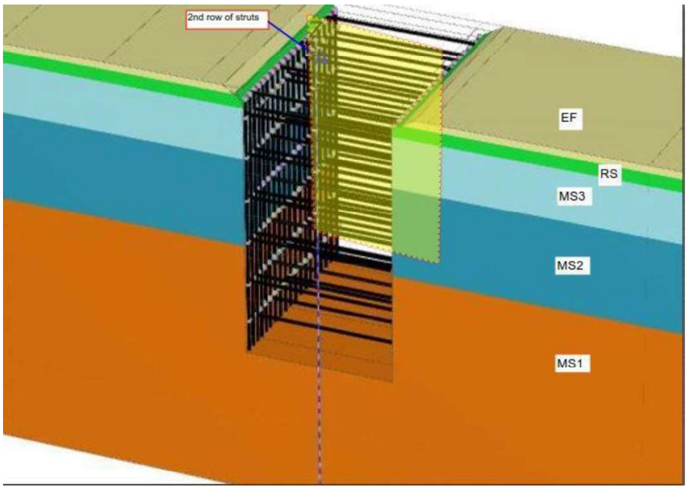

Figure 3. Plaxis 3D model.

Table 1. Geotechnical units.

Geotechnical Unit	Description	Thickness (m)
1	Engineered Fill (EF)	1.0
2	Residual Soil (RS)	2.0
3a	MS3	8.0
3b	MS2	14
3c	MS1	40*

* Bottom boundary of finite element model

Table 2 summarises the geotechnical properties adopted in the Plaxis analyses. The Hardening soil model was used to simulate both soil and weathered rock materials.

Table 2. Geotechnical properties.

Unit	Description		E_{50}	E_{ur}	c'	'	k_o
1	EF	20	40	120	0	34	0.44
2	RS	20	25	75	10	32	0.47
3a	MS3	22.5	100	300	37	30	0.6
3b	MS2	23	200	1200	60	34	1.2
3c	MS1	24	800	2800	115	43	1.5

= Unit weight (kN/m3)
E_{50} = Secant modulus at 50% strength (MPa)
E_{ur} = Unloading-reloading modulus (MPa)
c' = Effective cohesion (kPa)
' = Effective friction angle (degree)
k_o = At rest coefficient of earth pressure

4.3 *Structural model*

The bored pile stiffness adopted in the analysis was taken as 70% of uncracked pile stiffness (E_c = 32 GPa).

The axial stiffness of struts (E_sA_s) was 4.6E7 kN and the flexural stiffness of walers (E_wI_w) was 8.5E6 kN-m2.

Piles were modelled using beam elements in Plaxis3D and plate elements in Plaxis2D. Stiffness of the plate elements in Plaxis2D had been adjusted with the actual pile spacing to account for the three-dimensional condition of the piles.

4.4 *Construction sequence in Plaxis model*

The construction sequence modelled in the analyses is illustrated in Figure 4 below. Excavation to 2 m below strut level was assumed in the model.

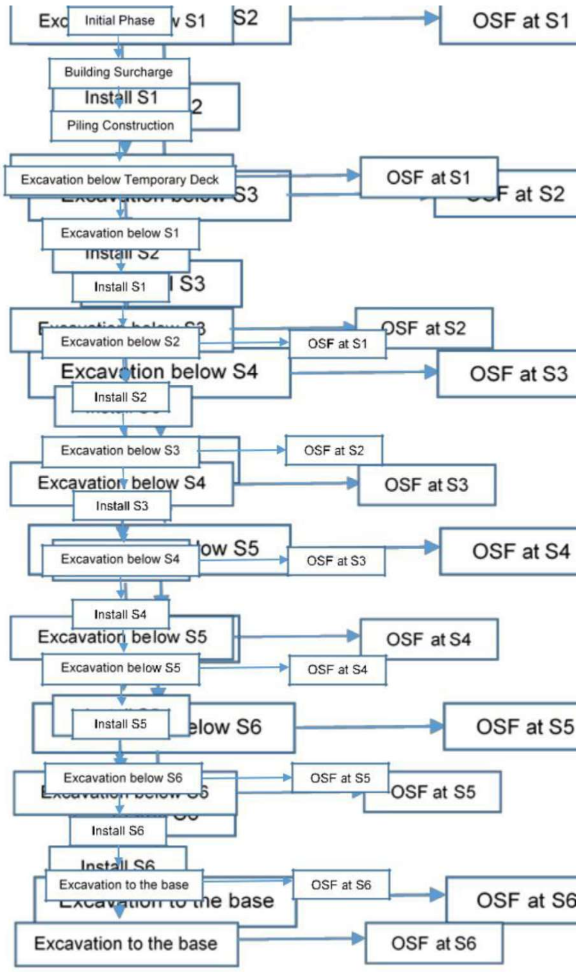

Figure 4. Construction sequence in Plaxis analysis.

5 NUMERICAL CASES

Both Plaxis3D and Plaxis2D analyses have been performed. To achieve the objectives of the present study, the following cases have been analysed:

- Case 1: Base case without OSF. In this case, excavation was carried out until the bottom of excavation. Both bending moments in the piles and forces in the struts are compared.
- Case 2: Plaxis3D with OSF cases. This case focused on the redistribution of forces from the removed strut to the adjacent struts in both horizontal and vertical directions.
- Case 3: Comparison of Plaxis3D and Plaxis2D for OSF at strut S2. Excavation reached below strut S3 level but before the commencement of installation of Strut S3.
- Case 4: Comparison of Plaxis3D and Plaxis2D for OSF at strut S3. Excavation reached below strut S4 level but before the commencement of installation of Strut S4.
- Case 5: Comparison of Plaxis3D and Plaxis2D for OSF at strut S4. Excavation reached below strut S5 level but before the commencement of installation of Strut S5.
- Case 6: Comparison of Plaxis3D and Plaxis2D for OSF at strut S5. Excavation reached below strut S6 level but before the commencement of installation of Strut S6.

Note that OSF at strut S1 was not discussed here as this refers to the distribution of loads to the temporary deck, the stiffness of which is different from other struts.

Similarly, OSF at strut S6 is also not discussed as its stiffness is also different from others.

Parametric studies were undertaken in 2D by varying the stiffness of the strut removal layer. The results of the parametric studies are then compared with Plaxis3D analysis results.

6 RESULTS

6.1 *Case 1 – Base case without OSF*

Figure 5 presents comparison of the bending moments in the piles at the final stage (excavation to the base).

The bending moments obtained from the Plaxis2D analysis agree with those from the Plaxis3D analysis as shown in Figure 5.

The strut forces estimated from both analyses only differ slightly (between -5% and 12%) as presented in Table 3. In general, the Plaxis2D analysis overestimates the strut forces.

6.2 *Case 2 – Plaxis3D with OSF cases*

When a strut is removed, its load will be redistributed to adjacent struts, laterally to the struts in the same layer and vertically to the above struts. The load distributed to adjacent struts can only be calculated using a three-dimensional analysis. This section discusses the results of the redistribution of the load of the removed strut obtained from Plaxis3D analyses.

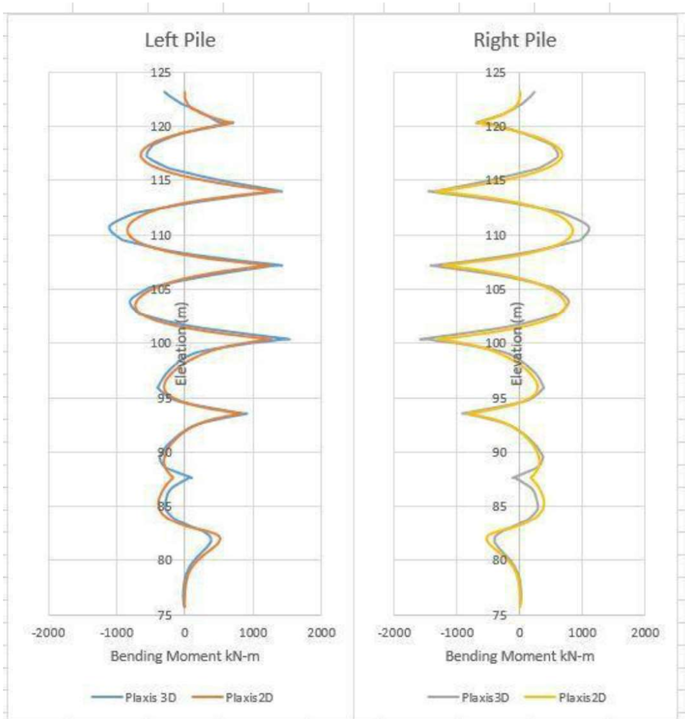

Figure 5. Bending Moment Comparisons calculated from Plaxis3D and Plaxis2D.

Table 3. Comparison of strut loads (in kN) – without OSF

Description	Strut No	Plaxis2D	Plaxis3D	Differences
Below S2		3643	3434	6.1
Below S3	S1	4711	4280	10.1
	S2	6332	5784	9.5
Below S4	S1	5345	4803	11.3
	S2	8669	7791	11.3
	S3	6349	6593	-3.7
Below S5	S1	5879	5291	11.1
	S2	10469	9366	11.8
	S3	9491	9860	-3.7
	S4	6707	6887	-2.6
Below S6	S1	6223	5661	9.9
	S2	11631	10440	11.4
	S3	11491	12013	-4.3
	S4	9924	10345	-4.1
	S5	6585	6875	-4.2

Table 4. Redistribution of strut loads (in %)

Description	Strut No	2nd row(1)	1st and 3rd row(2)
OSF at S2 (case 3)	S1	29.1%	15.7%
	S2	Removed	55.2%
OSF at S3 (case 4)	S2	15.8%	21.6%
	S3	Removed	62.6%
OSF at S4 (case 5)	S3	20.5%	29.0%
	S4	Removed	50.5%
OSF at S5 (case 6)	S4	20.2%	28.7%
	S5	Removed	51.1%

Notes:

(1) 2nd row are the struts installed within the same vertical plane that encompasses the removed strut

(2) 1st and 3rd row are the struts installed on both sides of 2nd row struts

Table 4 summarises the load redistribution (in per-centage) from the removed strut to the adjacent struts for each OSF case.

The above findings should be taken into consideration when assessing results from 2D analyses for OSF cases as the 2D analysis can only estimate vertical load redistribution, but no lateral load redistribution.

The results show that 50% to 63% of the removed strut load is redistributed to lateral struts and between 16% and 30% is redistributed to the vertical struts.

6.3 *Case 3 – OSF at Strut S2*

For Case 3 to Case 6, increase in load of the strut above the removed strut is normalised to a percentage ratio of the loads in the strut post and pre strut removal. This ratio overcomes slight differences of the loads predicted from the Plaxis2D and Plaxis3D analyses as discussed in Section 6.1.

The results are presented in terms of percentage increase in load of the adjacent strut versus parameter *m*.

Figure 6 shows that the load of the strut (S1) above the removed strut (S2) increases 20% from the Plaxis3D analysis.

The Plaxis2D parametric analyses show that choosing *m* value of 0.76 or reducing the stiffness of strut S2 by 50% agrees with the increase in load of Strut S1 estimated from Plaxis3D analysis.

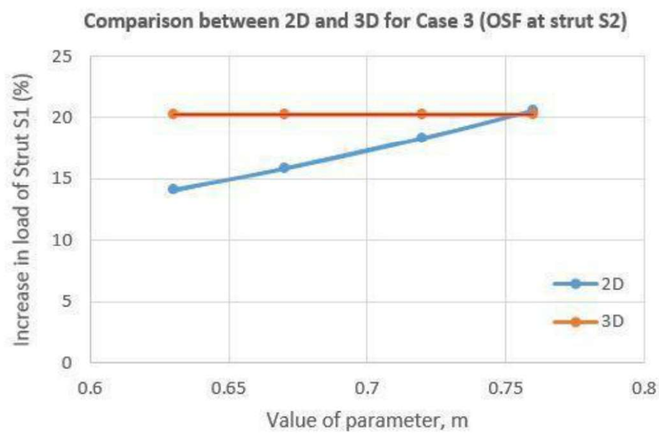

Figure 6. Load Increase in Strut S1 versus *m* values

6.4 *Case 4 – OSF at Strut S3*

Figure 7 shows that the increase in load of strut S2, installed above the removed strut (S3), is only 6% from Plaxis3D analysis. Such small increase in load of strut S2 is due to the position of Strut S3 which is installed within MS2 rock. MS2 has stiffer properties compared to the soil/rock materials above. Refer to the redistribution of strut loads in Table 4, the load in strut S2 only increases 15.8% compared to the load increase in Strut S1 of 29% (in case 3).

Plaxis2D parametric analyses show that no *m* value converges to the same increase in load of strut S2 as obtained from Plaxis3D analysis. This correlates with a reduction of the stiffness of strut S3 of 10% only.

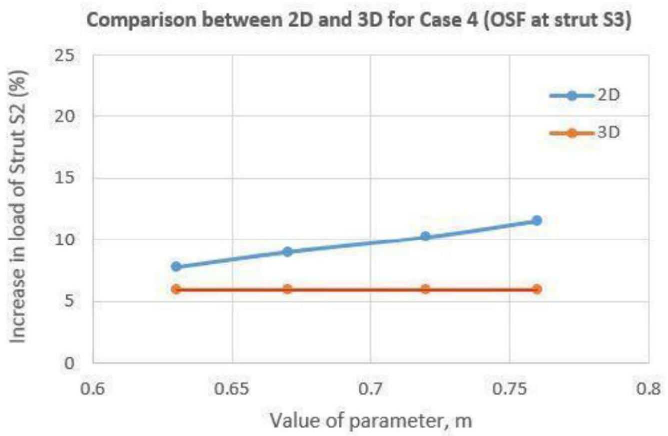

Figure 7. Load Increase in Strut S2 versus *m* values

6.5 *Case 5 – OSF at Strut S4*

Similar results were also obtained for Case 5. Strut S4 is located near the interface between MS2 and very strong MS1 rocks. There is only small increase of load in Strut S3 (only 5 %) as shown in Figure 8.

Plaxis2D parametric analyses show that there is no *m* value that produces results that match the results of Plaxis3D analysis. This indicates that Plaxis2D analyses overestimate the loads for OSF cases.

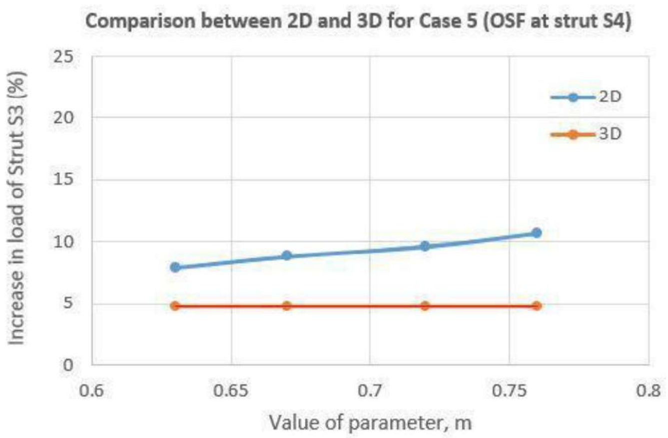

Figure 8. Load Increase in Strut S3 versus *m* values

6.6 *Case 6 – OSF at Strut S5*

Similar results were also obtained for Case 6. Strut S5 is located well below within the very strong MS1 rock. There is only a small increase of load in Strut S4 (only 4 %) as shown in Figure 9.

Plaxis2D parametric analyses show that there is no *m* value that matches the results of Plaxis3D analysis. This indicates Plaxis2D analyses overestimate loads for OSF cases.

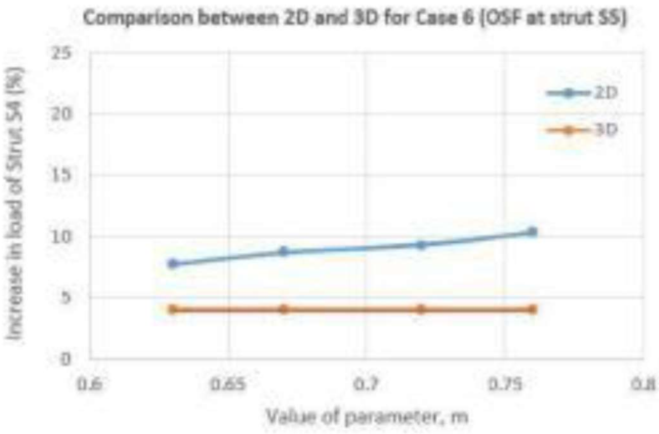

Figure 9. Load Increase in Strut S4 versus *m* values

7 CONCLUSION

The findings of the analyses presented in this paper are summarised below:

- Two dimensional analysis can be used to analyse one strut failure (OSF) case. However, it should be undertaken with caution as 2D analysis can only estimate vertical load redistribution, but no lateral load redistribution.
- The proposed approach described in Section 2.3 can be used to estimate the reduced stiffness of the strut removal layer.
- Location of struts with respect to the soil/rock materials behind the wall affects the load redistribution predicted using the Plaxis2D analysis. In general, the loads predicted by Plaxis2D analyses are larger than those predicted by 3D analyses for those cases where struts supporting stronger soil/rock materials behind them.

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