International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 09 Issue: 12 | Dec 2022 www.irjet.net p-ISSN: 2395-0072

Analytical Study on Impact of One Strut Failure Condition on Soil Support System of Underground Works

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Abstract: *For a robust design of ERSS as recommended by many authors and references i.e., CIRIA C517, CIRIA C760, the One strut failure (OSF) case is an important criterion to analyse. OSF condition is a condition when any one strut, anchor, or tieback of an ERSS system at any one location fails, then the additional load from this failed strut, shall be safely undertaken by other part of the structure and thus the temporary earth support system remains stable and the catastrophic action can be safely avoided. This paper undertakes comparative analysis of ERSS system adopted for cut and cover station works of underground Metro project in Mumbai. The OSF condition is simulated in the structural model where a single strut at a level is deactivated and structure is analysed and similarly, stimulating the same condition at other respective levels for the study of force distribution in the whole system. The analysis results of 3 different models are compared to understand the increased load distribution, due to the failure of one strut, to the adjacent struts. The results obtained can further be analysed to optimize project timeline and cost at sites where it becomes difficult to carry out the construction with the 'struts in position". This idea was recommended in one of the research papers, but no study related to this is found.*

Keywords: Earth Retaining and Stabilizing System (ERSS), One strut failure (OSF)

1. INTRODUCTION

In April 2004 in Singapore, a catastrophic disaster happened due to collapse of 33.3 m deep excavation. The failure of 9th level strut was the reason of collapse (Whittle and Davis, 2006). This failure condition termed as one strut failure (OSF) design condition was introduced in Singapore and Malaysia for any deep excavation works. For the underground excavations especially for the Metro projects the main concern lies about the stability of the excavated surface to carry out the construction activities uninterrupted for a long duration till construction progresses to Ground level. The design of deep excavation shall be such as to accommodate the possible failure of any strut, structural member, or connection at any stage of construction works. The wall and remaining support system shall be capable to stand safe and be able to carry additional load transferred due to failed strut/ connection. This leads to the special design condition called as one strut failure case.

The ERSS system should be such that gives sufficient redundancy to avoid any catastrophic collapse of the system due to overloading locally or failure of any particular support element. Overall failure of the system occurs due to inadequate strutting or passive soil failure if the wall embedment/ key-in depth is inadequate. The inadequacy of the strutting system may also be due to bad connection details of strut to waler or waler to wall causing disproportionate load distribution in the system. Due to failure of a single strut the load of the failed strut is redistributed to the adjacent struts (vertical, horizontal and to diagonal struts) which may exceed the section design capacity thus resulting in the progressive failure of whole strutting system. And therefore, leading to the increased cost of the project. This paper presents the analytical study of Mumbai underground Metro deep excavation and soil support system to understand the lateral force distribution in the strut using the software STAAD and WALLAP. The design comparison is made for the two analysis conditions – normal case and OSF case. The argument generally comes across is the cost impact on the project due to OSF design condition, this aspect is analysed and presented by performing the section design capacity check as per Codal requirements.

2. LITERATURE REVIEW

Initial studies were focused on analysing deep excavation soil support system for clay, sand etc, Then other parameters affecting the soi support system say pile diameter, wall/ pile embedment depths etc. were analysed and presented.

Author	Description of Findings
Peck (in 1969)	Presented that lateral earth pressure is the load for analysis and design of deep excavation
Liao and Neff (in 1990)	Highlighted limitations and enhancement of Peck's findings
Hashash and Whittle (in 2002)	Proposed a controlled mechanism for lateral earth pressure around braced excavation in clay
Stille and Broms(in 1976)	Presented failure analysis of the anchor.
Puller (in 2003)	Presented that overall failure could be due to inadequate strutting or passive soil failure due to inadequate embedment of the retaining wall/ pile
K. F. Pong, S. L. Foo, C. G. Chinnaswamy, C. C. D Ng & W. L. Chow (in 2012)	Presented his findings by comparing the analysis of OSF condition with 3D approach and 2D plain strain analysis. Author concluded that - 1) Diaphragm wall design is governed by normal case and least affected with OSF condition 2) 2D numerical analysis though conservative is appropriate to consider
David C. C. Ng and Simon Y. H. Low2 (in 2016)	Proposed to omit one strut using observational approach to optimise the construction time and cost. Instrumentation monitoring and actual behavior of soil support system are instrumental in this approach of OSF.
A.T.C Goh3, Zhang Fan4, Liu Hanlong1.2, Zhang Wengang1.2 and Zhou Dong2 (in 2018)	Presented numerical analysis strut responses under OSF condition in clay. 2D and 3D analysis is done for the comparison. Strut response due to OSF is demonstrated as - Load transfer (%) = $\frac{\text{Npost-Npre}}{\text{Nfail}} \times 100\%$ Where, Npost – strut load post the strut failure, Npre – strut load before the strut failure Nfail – load on failed strut before strut failure
Kamchai Choosrithong and Helmut F. Schweiger (in 2018)	Presented numerical investigation for OSF in soft soil using PLAXIS software for geotechnical analysis. Diaphragm wall is analysed for 2 different embedment depths – i) wall with uniform embedment along the wall length ii) wall with uneven embedment depths along the wall length
S. S. Gue, C. S. Gue and C. Y. Gue (in 2018)	Presented design principles of ERSS with vertical rock excavation. Author concluded that- 1) due to failed strut the strut forces in adjacent struts increases by 50% 2) due to failed strut the BM in waler increases by 400% unlike increase in strut forces. 3) if OSF case is considered in the analysis, accidental impact case is no longer relevant.
Hai K. Phan[1], B. C. Hsiung[1], and J. Huang[2] (in 2019)	1) also emphasized on OSF case analysis of the system as it can lead to overall failure of the deep excavation. 2) additional load due to failed strut to one strut above is 50% 3) if the strut is located at the corner the additional load due to failed strut to one strut above is 110%, but the magnitude of the force still remains less.
Kamchai Choosrithong and Helmut F. Schweiger (in 2020)	Presented a paper on numerical investigation of sequential strut failure on performance of deep excavation.
Jianhua LIU[3], Shaoming WU[3], Linfeng WANG[b,c,1] and Xiaohan ZHOU[b,c] (in 2021)	Analysed the soil support system for 2 conditions - 1) failure of single strut, struts are removed one by one to study it's effect on other struts 2) continuous failure of multiple struts, when the increased load of a strut exceeds it's design capacity the struts starts failing one after another. due to this progressive failure of struts the displacement of surrounding soil increases successively

Table 1: Summary of Authors findings

3. OBJECTIVES OF PRESENT STUDY

This paper focuses on following objectives -

To prepare construction stage model for the actual on-site excavation (for Mumbai underground project) and available soil data using software WALLAP (is a software by Geosolve used to analyze retaining walls including cantilever wall, anchored wall, and strutted excavations for cut and cover underground stations). From analysis will determine the magnitude of load acting at each strut and waler level.

1) The structural model will be analysed for two conditions - normal case and one strut failure (OSF) case.
2) To analytically determine the lateral force distribution in the strut and waler using the software STAAD.
3) To outline the forces comparison of struts and walers under two different analysis cases.
4) To design the strut sections for obtained design forces for two conditions for comparison of section capacity.

4. ANALYSIS METHODOLOGY

To understand the load distribution in the ERSS system due to failure of a strut at any level in the system, the structure is analysed using software STAAD. The lateral load at each strut/ waler level for the STAAD analysis is evaluated from the Geotechnical model prepared in WALLAP using onsite excavation data and soil parameters.

Geotechnical data of deep excavation works of an underground metro station works is used to analyse the structure for the 2 loading conditions as described below.

3D analysis of the earth support system is analysed with secant pile wall depth up to the embedment depth. Analysis is done for the part structure considering the repetition of the framing system along the length of the excavation which is approximately 200m ~ 230m and excavation width is of 25m ~ 30m. Strut with splay, waler beam and secant pile wall is modeled as the beam member having relevant material properties and the size.

Two conditions are considered for structural analysis in STAAD –

1) Force distribution under Normal case
   - ✓ For the strut at different levels
   - ✓ For the strut at same level
   - ✓ For the walers at all levels
2) Force distribution under OSF case
   - ✓ For the strut vertically above/ below the failed strut level
   - ✓ For strut horizontally along the failed strut
   - ✓ For the walers at failed strut level

The data required for this analysis is referred from the underground excavations of the Cut and Cover Metro Stations. The typical framing plan of a model at Strut level 1 and Strut level 2 is shown in fig.1. Struts are placed at 9m c/c horizontally along the length of the excavation, the struts are supported additionally by plunge columns and end supports are secant pile. Rectangular marked area is considered in STAAD analysis. Retaining wall is a concrete secant pile wall. Three models of 3 different locations are analysed and resultant forces are compared for the study of load distribution in the adjacent struts due to a failed strut at a level.

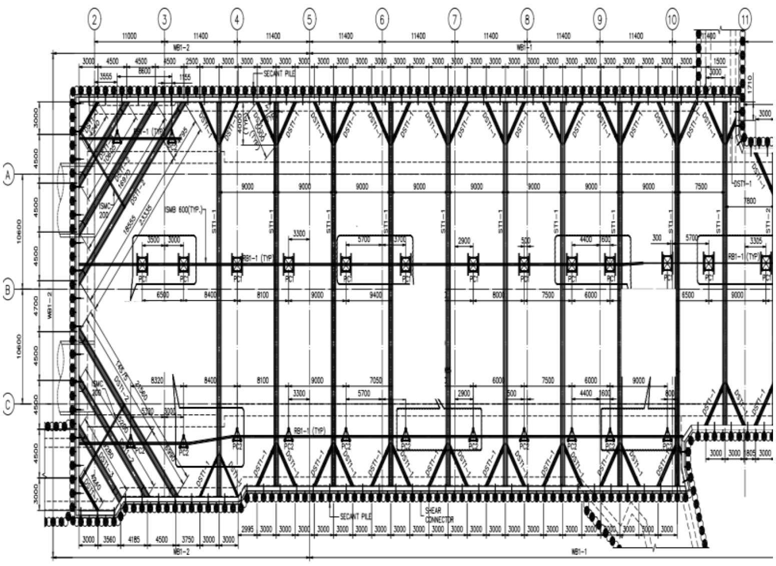


Fig1: Plan of a soil support system

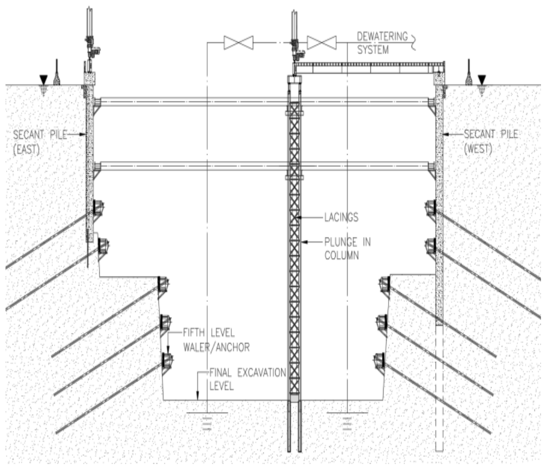


Fig.2: Section of soil support system

4.1 WALLAP MODEL: The WALLAP model is used depicting the soil strata of the excavation, construction sequence, applying soil parameters, secant wall properties, surcharge load, earth pressure and water pressure etc. The software checks the stability of the structure and gives the analysis results as values of structural forces at all construction stages.

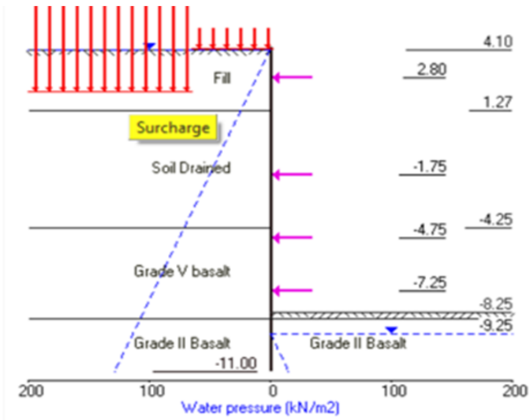


Fig. 3: Typical Construction stage model for Normal Case in Wallap

Construction stage no.	Stage description
1	Apply water pressure profile no.1
2	Change EI of wall to 77330 kN.m2/m run
	From elevation -8.50 to -9.00
	Yield moment not defined
	Allow wall to relax with new modulus value
3	Change EI of wall to 11011 kN.m2/m run
	From elevation -9.00 to -11.00
	Yield moment not defined
	Allow wall to relax with new modulus value
4	Apply surcharge no.1 at elevation 4.10
5	Apply surcharge no.2 at elevation 2.10
6	Apply water pressure profile no.2
7	Excavate to elevation 1.80 on RIGHT side
8	Install strut or anchor no.1 at elevation 2.80
9	Apply water pressure profile no.3
10	Excavate to elevation -2.75 on RIGHT side
11	Install strut or anchor no.2 at elevation -1.75
12	Apply water pressure profile no.4
13	Excavate to elevation -5.75 on RIGHT side
14	Change properties of soil type 2 to soil type 6
15	Install strut or anchor no.3 at elevation -4.75
16	Apply water pressure profile no.6
17	Excavate to elevation -8.25 on RIGHT side
18	Install strut or anchor no.4 at elevation -7.25
19	Apply water pressure profile no.5
20	Excavate to elevation -8.50 on RIGHT side
21	Install strut or anchor no.5 at elevation 2.78
22	Remove strut or anchor no.1 at elevation 2.80

Fig.4:Typical Construction sequence for OSF case with 1stlevel level strut failure in Wallap

Construction stage no.	Stage description
1	Apply water pressure profile no.1
2	Change EI of wall to 77330 kN.m2/m run
	From elevation -8.50 to -9.00
	Yield moment not defined
	Allow wall to relax with new modulus value
3	Change EI of wall to 11011 kN.m2/m run
	From elevation -9.00 to -11.00
	Yield moment not defined
	Allow wall to relax with new modulus value
4	Apply surcharge no.1 at elevation 4.10
5	Apply surcharge no.2 at elevation 2.10
6	Apply water pressure profile no.2
7	Excavate to elevation 1.80 on RIGHT side
8	Install strut or anchor no.1 at elevation 2.80
9	Apply water pressure profile no.3
10	Excavate to elevation -2.75 on RIGHT side
11	Install strut or anchor no.2 at elevation -1.75
12	Apply water pressure profile no.4
13	Excavate to elevation -5.75 on RIGHT side
14	Change properties of soil type 2 to soil type 6
15	Install strut or anchor no.3 at elevation -4.75
16	Apply water pressure profile no.6
17	Excavate to elevation -8.25 on RIGHT side
18	Install strut or anchor no.4 at elevation -7.25
19	Apply water pressure profile no.5
20	Excavate to elevation -8.50 on RIGHT side
21	Install strut or anchor no.5 at elevation -1.72
22	Remove strut or anchor no.2 at elevation -1.75

Fig.5:Typical Construction sequence for OSF case with 2nd strut failure inWallap

4.2 Staad model data:

1) Excavation Depth : of ~15tm, 12m, 22.4m (depth up to excavation level)
2) Excavation Size in plan: width of 36m, 21.4m, 22.4m and length only part of the total excavation (250m)
3) Secant pile diameter : 800 mm (both primary and secondary piles)
4) Strut (with splays) : Steel UB Sections, 2 strut levels at 9m c/c with anchors spaced at 2.6m c/c at lower leve;s
5) Waler : Steel UB/ ISMB section, spanning 2.6m c/c
6) Soil parameters : as per the Geotechnical report
7) Water Table: as per the Geotechnical report

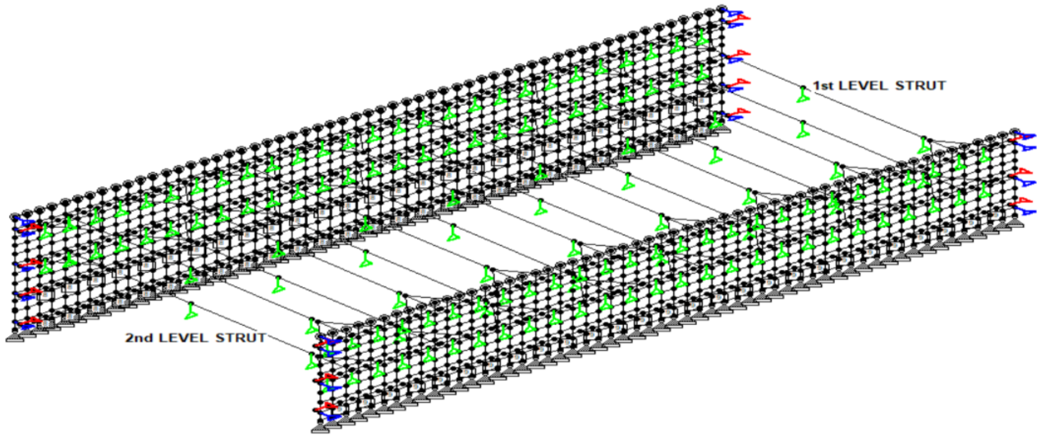
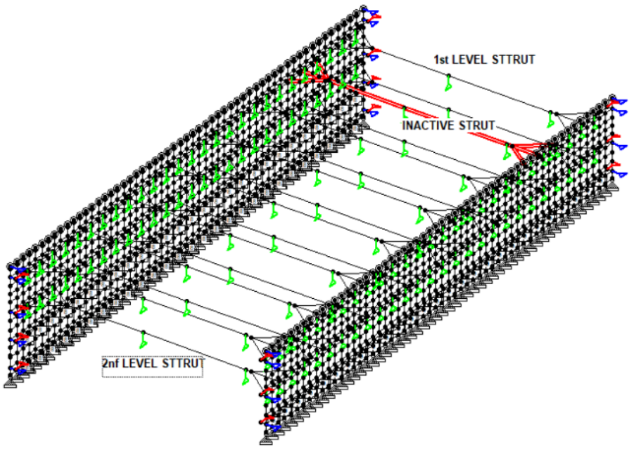


Fig.6: Staad model for Normal case



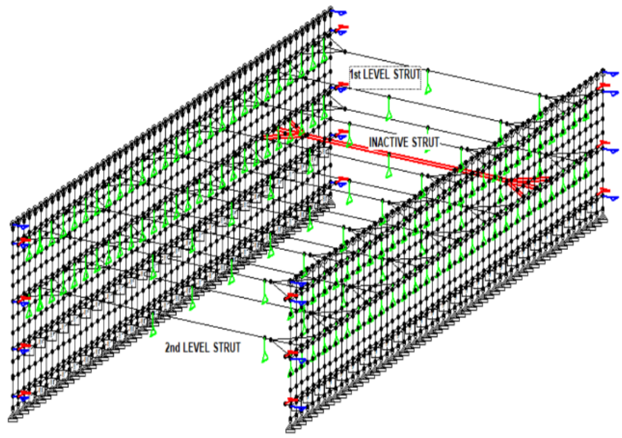


Fig.7: Staad model for OSF case – 1st level strut deactivated Fig.8: Staad model for OSF case – 2nd level strut deactivated

5. DESIGN LOADS AND PARTIAL SAFETY FACTOR FOR THE DESIGN LOADS FOR ERSS SYSTEM

Different loads for the analysis of a soil support system are -

a) earth pressures
b) groundwater
c) material dead load, and ground surcharge
d) live load, eccentric load, surcharge load
e) temperature effect
f) accidental impact load
g) one-strut failure.

Load Case	EL	DL	LL	TL	IL
Working Condition	1.5	1.4	1.6	1.2	NA
Accidental Impact	1.05	1.05	0.5	NA	1.05
One-strut Failure	1.05	1.05	0.5	NA	NA
Note: EL – Earth pressure and groundwater DL – Dead load LL – Live load TL – Temperature effect IL – Accidental impact load NA – Not applicable					

Table 2: recommended partial safety factors for the member design

In this paper for the comparative analysis of the load distribution due to a failed strut under Normal case and OSF case loading condition the temperature effect, accidental load are ignored. Moreover, when checking the system for the critical case of OSF, temperature load is not applicable as per Table 2.

6. RESULTS AND DISCUSSION

The members that are adjacent to the strut member considered deactivated in the analysis for both the conditions of OSF are tabulated below to read the forces from the Table 3, 4 & 5.

		AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN		
strut	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE
a	1257	949	948	949	1322	1854	1856	1855
	1332	2121	2113	2117	12585	3258	3255	3253
	12583	2121	2113	2117	12601	3258	3255	3253
	1256	2121	2113	2117	1320	3258	3255	3253
	1255	777	774	777	1319	1600	1600	1602
b	7880	933	938	931	7893	1721	1721	1714
	7900	2161	2173	2172	12587	3825	3838	3830
	12586	2161	2173	2172	12602	3825	3838	3830
	7878	2161	2173	2172	7891	3825	3838	3830
	7877	674	670	678	7890	1520	1512	1519
c	7910	849	855	836	7921	1756	1778	1754
	7926	2021	1975	2004	12589	3740	3716	3716
	12588	2021	1975	2004	12603	3740	3716	3716
	7908	2021	1975	2004	7919	3740	3716	3716
	7907	702	682	711	7918	1638	1640	1656
d	7936	799	840	778	7949	1716	1704	1679
	7956	2035	2167	2074	12591	3797	3849	3865
	12590	2035	2167	2074	12604	3797	3849	3865
	7934	2035	2167	2074	7947	3797	3849	3865
	7933	739	732	759	7946	1665	1614	1659
e	7966	798	797	764	7979	1713	1777	1775
	7986	2042	1699	1947	12593	3803	3675	3620
	12592	2042	1699	1947	12605	3803	3675	3620
	7964	2042	1699	1947	7977	3803	3675	3620
	7963	740	686	756	7976	1664	1691	1763
f	7995	841	684	837	8006	1759	1671	1228
	8012	2001	2868	2001	12595	3734	3745	4295
	12594	2001	2868	2001	12606	3734	3745	4295
	7993	2001	2868	2001	8004	3734	3745	4295
	7992	699	618	613	8003	1646	1528	1248
g	8022	932	0	1914	8035	1718	2684	0
	8042	2203	0	3835	12597	3845	5803	0
	12596	2203	0	3835	12607	3845	5803	0
	8020	2203	0	3835	8033	3845	5803	0
	8019	675	0	1449	8032	1514	2808	0
h	8049	972	810	993	8056	1914	1794	1349
	8060	2028	3128	2094	12599	3265	3342	3912
	12598	2028	3128	2094	12608	3265	3342	3912
	8048	2028	3128	2094	8055	3265	3342	3912
	8047	796	746	697	8054	1616	1492	1166

increased forces in adjacent struts f and h horizontally @ level 1 and strut g vertically @ level 2 due to OSF case
increased forces in adjacent struts f and h horizontally @ level 2 and strut g vertically at level 1 due to OSF case
slight decrease in 1st level strut due to OSF case of 1st level & OSF case of 2nd level

Table 3: Strut member analysis result for Model-1 for normal case, OSF case at level 1, OSF case at level 2

	AXIAL FORCES IN 1st LEVEL STRUT , kN					AXIAL FORCES IN 2nd LEVEL STRUT , kN					AXIAL FORCES IN 3rd LEVEL STRUT , kN				
Strut Name	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE
a	2364	507	623	508	596	2394	263	261	263	196	2838	803	819	803	774
	3220	125	444	125	134	3223	1407	1499	1408	1418	3226	2659	2573	2659	2701
	2363	125	444	125	134	2393	1407	1499	1408	1418	2837	2659	2573	2659	2701
	2357	1442	1311	1441	1524	2389	1776	1759	1776	1818	2830	1735	1733	1735	1761
b	2372	368	0	371	432	2396	300	534	294	346	2840	865	606	861	929
	3221	1862	0	1862	1836	3224	2449	4357	2449	2343	3227	4507	4174	4507	5574
	2371	1862	0	1862	1836	2395	2449	4357	2449	2343	2839	4507	4174	4507	4517
	2358	319	0	318	403	2390	469	1427	470	530	2831	1579	1340	1578	1672
c	2382	1331	1137	1332	1385	2398	1313	1267	1314	1183	2842	2257	2272	2256	1870
	3222	1273	1634	1273	1154	3225	2014	2161	2013	2124	3228	5170	5114	5171	5574
	2381	1273	1634	1273	1154	2397	2014	2161	2013	2124	2841	5170	5114	5171	5574
	2359	613	757	614	680	2391	16	41	16	130	2832	1816	1807	1815	1611
d	7265	1331	1330	1332	1045	7272	1158	1184	1160	3182	7279	2417	2419	2417	0
	7284	1256	1088	1257	633	7285	1872	1808	1872	5026	7286	5481	5468	5482	0
	7264	1256	1088	1257	633	7271	1872	1808	1872	5026	7278	5481	5468	5482	0
	7263	601	598	603	1194	7270	97	68	97	1472	7277	1934	1943	1933	0
e	7295	931	935	933	999	7302	954	946	957	826	7309	2685	2675	2684	2630
	7314	1328	1382	1327	1200	7315	1874	1905	1873	1961	7316	5040	5040	5038	5499
	7294	1328	1382	1327	1200	7301	1874	1905	1873	1961	7308	5040	5040	5038	5499
	7293	173	173	176	273	7300	109	98	109	38	7307	1736	1725	1734	1537
f	7337	701	704	702	714	7344	1010	1016	1012	1038	7351	562	566	561	611
	7356	1609	1592	1612	1603	7357	2477	2468	2479	2359	7358	2334	2329	2335	2293
	7336	1609	1592	1612	1603	7343	2477	2468	2479	2359	7350	2334	2329	2335	2293
	7335	322	320	319	328	7342	847	848	845	868	7349	990	991	988	1051
g	7379	405	408	406	387	7386	846	846	850	821	7393	788	787	789	786
	7398	1671	1676	1664	1678	7399	2564	2568	2558	2577	7400	2168	2170	2165	2211
	7378	1671	1676	1664	1678	7385	2564	2568	2558	2577	7392	2168	2170	2165	2211
	7377	614	612	612	625	7384	955	951	957	949	7391	805	803	805	810
h	7421	307	309	305	285	7428	801	803	795	786	7435	702	703	695	706
	7440	1661	1659	1682	1651	7441	2587	2586	2604	2575	7442	2074	2073	2082	2085
	7420	1661	1659	1682	1651	7427	2587	2586	2604	2575	7434	2074	2073	2082	2085
	7419	722	721	721	744	7426	1047	1045	1041	1061	7433	801	801	795	818
i	7463	293	295	293	271	7470	794	795	815	776	7477	657	657	671	655
	7482	1702	1703	1653	1703	7483	2635	2636	2588	2635	7484	2003	2003	1972	2013
	7462	1702	1703	1653	1703	7469	2635	2636	2588	2635	7476	2003	2003	1972	2013
	7461	742	742	749	764	7468	1064	1062	1089	1074	7475	766	766	782	776
j	7505	334	336	295	317	7512	849	850	695	836	7519	659	659	618	657
	7524	1647	1647	1645	1645	7525	2607	2607	2707	2605	7526	1918	1918	2002	1921
	7504	1647	1647	1645	1645	7511	2607	2607	2707	2605	7518	1918	1918	2002	1921
	7503	709	709	684	727	7510	1071	1070	928	1081	7517	747	747	706	756
k	7529	392	393	1108	382	7536	838	838	0	829	7543	608	608	1344	606
	7548	1817	1817	3151	1817	7549	2763	2764	0	2764	7550	1956	1956	3317	1958
	7528	1817	1817	3151	1817	7535	2763	2764	0	2764	7542	1956	1956	3317	1958
	7527	635	635	1405	646	7534	976	975	0	982	7541	664	663	1435	668
l	7553	546	547	534	544	7560	1020	1020	878	1017	7567	722	722	688	722
	7572	1489	1488	1639	1489	7573	2324	2325	2488	2325	7574	1616	1616	1742	1615
	7552	1489	1488	1639	1489	7553	2324	2325	2488	2325	7566	1616	1616	1742	1615
	7551	630	631	617	634	7558	1063	1062	928	1064	7565	726	725	689	728

- increased forces in adjacent struts a and c horizontally @ level 1 and strut b vertically @ level 2 and level 3 due to OSF case when strut b at 1st level is made inactive in staad
- increased forces in adjacent struts j and l horizontally @ level 2 and strut k vertically @ level 1 and level 3 due to OSF case when strut k at 2nd level is made inactive in staad
- increased forces in adjacent struts c and e horizontally @ level 3 and strut d vertically @ level 1 and level 2 due to OSF case when strut d at 3rd level is made inactive in staad
- slight decrease in 1st level strut due to OSF case of 1st level & OSF case of 2nd level

Table 4: Strut member analysis result for Model-2 for normal case, OSF case at level 1, OSF case at level 2

		AXIAL FORCES IN 1st LEVEL STRUT , kN					AXIAL FORCES IN 2nd LEVEL STRUT , kN					AXIAL FORCES IN 2nd LEVEL STRUT , kN			
Strut Name	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	MEMBER NO.	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE
a	3869	610	641	627	580	3981	1593	1640	1271	1617	4749	3142	971	1038	685
	4350	992	1363	1045	863	4369	1165	1225	1539	1224	4817	3190	1109	1322	1964
	4413	992	1363	1045	863	4439	1165	1225	1539	1224	4818	3141	1109	1322	1964
	3868	992	1363	1045	863	3979	1165	1225	1539	1224	4747	3141	1109	1322	1964
	3864	514	597	520	482	3978	1232	1200	1446	1277	4746	3140	1732	1750	2041
b	3878	433	0	967	392	3987	773	1446	0	1626	4755	3146	536	1483	0
	4352	1607	0	2842	1617	4360	3897	5423	0	5952	4813	3186	4494	6493	0
	4415	1607	0	2842	1617	4475	3897	5423	0	5952	4822	3152	4494	6493	0
	3885	1607	0	2842	1617	3994	3897	5423	0	5952	4762	3151	4494	6493	0
	3884	705	0	1282	698	3993	1072	1798	0	2176	4761	3150	1805	2973	0
c	3900	433	469	441	417	3999	1084	1084	943	1041	4767	3156	987	930	752
	4354	1188	1511	1326	1149	4362	2514	2670	2685	2650	4814	3187	2540	2741	2983
	4417	1188	1511	1326	1149	4441	2514	2670	2685	2650	4819	3155	2540	2741	2983
	3899	1188	1511	1326	1149	3997	2514	2670	2685	2650	4765	3154	2540	2741	2983
	3898	528	554	532	516	3996	781	778	671	726	4764	3153	722	633	332
d	3923	543	505	526	550	4028	905	904	923	926	4796	3167	696	706	737
	4356	1553	1430	1500	1555	4364	2982	2907	2898	2924	4815	3188	3170	3108	3004
	4419	1553	1430	1500	1555	4443	2982	2907	2898	2924	4820	3173	3170	3108	3004
	3922	1553	1430	1500	1555	4026	2982	2907	2898	2924	4794	3170	3170	3108	3004
	3921	599	558	583	600	4025	724	730	741	725	4793	3172	598	594	610
e	9202	678	684	679	679	9209	746	742	744	739	9220	5448	434	428	433
	9210	1891	1912	1909	1901	9211	3451	3464	3457	3470	9221	5456	3761	3774	3769
	9212	1891	1912	1909	1901	9213	3451	3464	3457	3470	9222	5454	3761	3774	3769
	9201	1891	1912	1909	1901	9208	3451	3464	3457	3470	9219	5451	3761	3774	3769
	9200	659	666	663	659	9207	591	589	590	580	9218	5453	505	495	504

Yellow	increased forces in adjacent struts a and c horizontally @ level 1 and strut b vertically @ level 2 and level 3 due to OSF case when strut b at 1st level is made i
Peach	increased forces in adjacent struts j and l horizontally @ level 2 and strut k vertically @ level 1 and level 3 due to OSF case when strut k at 2nd level is made
Light blue	increased forces in adjacent struts c and e horizontally @ level 3 and strut d vertically @ level 1 and level 2 due to OSF case when strut d at 3rd level is made
Light yellow	slight decrease in 1st level strut due to OSF case of 1st level & OSF case of 2nd level

Table 5: Strut member analysis result for Model-3 for normal case, OSF case at level 1, OSF case at level 2

The Staad analysis results are summarized in the table below for the strut member forces for all the three models analysed in Staad for Normal case and OSF case when the strut is inactive at level 1, OSF case when the strut is inactive at level 2, OSF case when the strut is inactive at level 3.

Model No.	AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 3rd LEVEL STRUT , kN			
	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE	NORMAL CASE	OSF @ LEVEL 1 CASE	OSF @ LEVEL 2 CASE	OSF @ LEVEL 3 CASE
Model 1	2203	3128	5803	0	3846	3835	4295	0	0	0	0	0
Model 2	1862	1817	4357	5468	2763	3151	2707	5482	5482	1836	5026	5574
Model 3	1891	1912	5423	4494	3897	2842	3457	6493	3186	1901	5952	3769

Table 6: Summary of Maximum Strut Forces (in adjacent horizontal and vertical struts of failed strut) for all 3 models

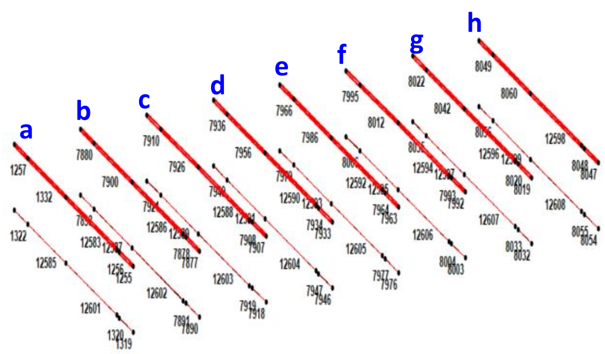


Fig9a: Strut numbering -Model 1

	Failed strut g at 1st level				Failed strut g at 2nd level			
	AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 1st LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load
Model 1	f	2001	2868	43.3	f	2001	2001	0.0
	h	2028	3128	54.2	h	2028	2094	3.3
	d	2035	2167	6.5	g	2203	3835	74.1
	e	2042	1699	-16.8	e	2042	1947	-4.7
	AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load
	f	3734	3745	0.3	f	3734	4295	15.0
	h	3265	3342	2.4	h	3265	3912	19.8
	g	3845	5803	50.9	d	3797	3865	1.8
	e	3803	3675	-3.4	e	3803	3620	-4.8

Table 7a: Model 1

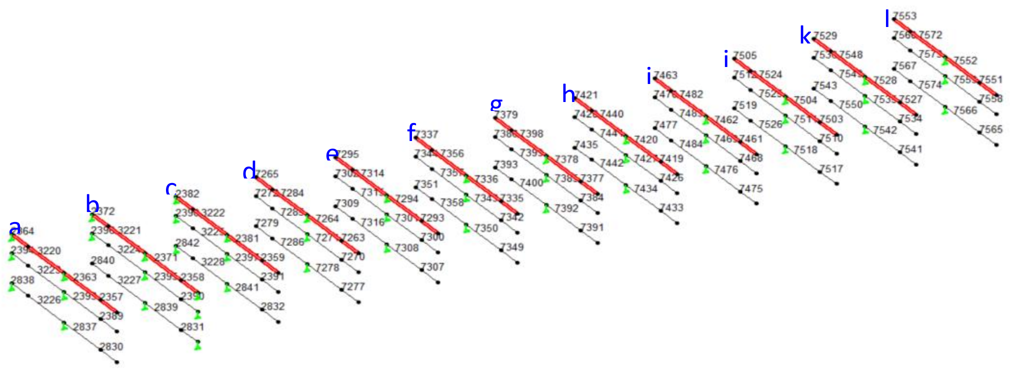


Fig9b: Strut numbering -Model 2

	Failed strut b at 1st level				Failed strut k at 2nd level				Failed strut d at 3rd level			
	AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 1st LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
Model 2	a	507	623	22.9	j	1647	1645	-0.1	d	1331	1385	4.1
	c	1273	1634	28.4	l	1489	1639	10.1	e	1328	1200	-9.6
	d	1256	1088	-13.4	k	1817	3151	73.4	d	1331	1045	-21.5
	g	1671	1676	0.3	i	1702	1653	-2.9	i	1702	1703	0.1
	AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
	a	1407	1499	6.5	j	2607	2707	3.8	c	2014	2124	5.5
	c	2014	2161	7.3	l	2324	2488	7.1	e	1874	1961	4.6
	b	2449	4357	77.9	h	2587	2604	0.7	d	1872	5026	168.5
	e	1874	1905	1.7	i	2635	2588	-1.8	f	2477	2359	-4.8
	AXIAL FORCES IN 3rd LEVEL STRUT , kN				AXIAL FORCES IN 3rd LEVEL STRUT , kN				AXIAL FORCES IN 3rd LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
	a	2659	2573	-3.2	j	1918	2002	4.4	c	5170	5574	7.8
	c	5170	5114	-1.1	l	1616	1742	7.8	e	5040	5499	9.1
	b	4507	4174	-7.4	k	1956	3317	69.6	b	4507	5574	23.7
	f	2334	2329	-0.2	i	2003	1972	-1.5	g	2168	2211	2.0

Table 7b: Model 2

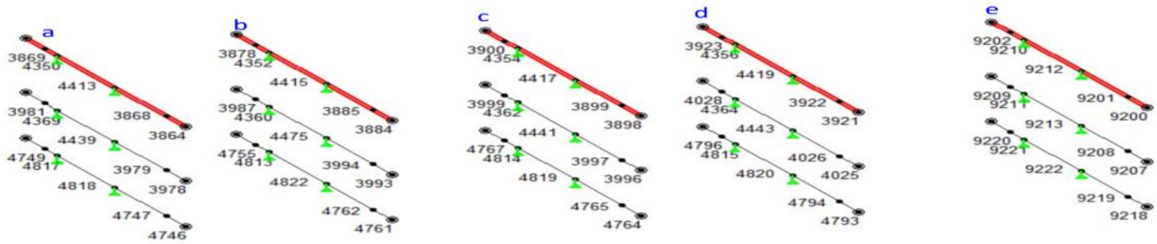


Fig9c: Strut numbering -Model 3

	Failed strut b at 1st level				Failed strut b at 2nd level				Failed strut b at 3rd level			
	AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 1st LEVEL STRUT , kN				AXIAL FORCES IN 1st LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
Model 3	a	992	1363	37.4	a	992	1045	5.3	a	992	863	-13.0
	c	1188	1511	27.2	c	1188	2685	126.0	c	1188	1149	-3.3
	d	1553	1430	-7.9	b	1607	2842	76.9	b	1607	1617	0.6
	e	1891	1912	1.1	d	1553	1500	-3.4	d	1553	1555	0.1
	AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN				AXIAL FORCES IN 2nd LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
	a	1165	1225	5.2	a	1165	1539	32.1	a	1165	1224	5.1
	c	2514	2670	6.2	c	2514	2685	6.8	c	2514	2650	5.4
	b	3897	5423	39.2	d	2982	2898	-2.8	b	3897	5952	52.7
	d	2982	2907	-2.5	e	3451	3457	0.2	d	2982	2924	-1.9
	AXIAL FORCES IN 3rd LEVEL STRUT , kN				AXIAL FORCES IN 3rd LEVEL STRUT , kN				AXIAL FORCES IN 3rd LEVEL STRUT , kN			
	Strut	NORMAL CASE	OSF @ LEVEL 1 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 2 CASE	% Increase in load	Strut	NORMAL CASE	OSF @ LEVEL 3 CASE	% Increase in load
	a	3141	1109	-64.7	a	3190	1322	-58.6	a	3141	1964	-37.5
	c	3155	2540	-19.5	c	3155	2741	-13.1	c	3155	2983	-5.5
	b	4813	4494	-6.6	b	3152	6493	106.0	d	3173	3004	-5.3
	d	3173	3170	-0.1	d	3173	3108	-2.0	e	5456	3769	-30.9

Table 7c: Model 3 (Table 7a, 7b, 7c: Summary of analysis results of each model for % load increase in struts adjacent to a failed strut at a level.)

	load case	Bending Moment My		Shear Fz		Axial		% increase in My	
		waler @ Level 1	waler @ Level 2	waler @ Level 1	waler @ Level 2	waler @ Level 1	waler @ Level	Waler @ Level 1	Waler @ Level 2
Model 1	Normal	295	777	396	815	100	331	-	-
	OSF @ 1st Level	470	1159	545	1440	542	667	59.3	49.2
	OSF @ 2nd Level	579	926	857	566	405	466	96.3	19.2

	load case	Bending Moment My			Shear Fz			Axial			% increase in My		
		waler @ Level 1	waler @ Level 2	waler @ Level	waler @ Level 1	waler @ Level 2	waler @ Level	waler @ Level 1	waler @ Level 2	waler @ Level 3	Waler @ Level 1	Waler @ Level 2	waler @ Level 3
Model 2	Normal	1094	1001	1091	487	346	702	1903	3123	2154	-	-	-
	OSF @ 1st Level	1207	1507	1174	420	359	543	2640	2857	2165	10.3	50.5	7.6
	OSF @ 2nd Level	1518	1367	1199	229	37	521	2641	2808	2178	38.8	36.6	9.9
	OSF @ 3rd Level	1177	1283	1114	485	360	821	1920	3167	2070	7.6	28.2	2.1

	load case	Bending Moment My			Shear Fz			Axial			% increase in My		
		waler @ Level 1	waler @ Level 2	waler @ Level	waler @ Level 1	waler @ Level 2	@ Level 3	waler @ Level 1	waler @ Level 2	waler @ Level 3	Waler @ Level 1	Waler @ Level 2	waler @ Level 3
Model 3	Normal	461	851	1831	502.6	347	652	740.2	960.6	954	-	-	-
	OSF @ 1st Level	533.1	879	1814	581.5	315	652	390	856.4	950	15.6	3.3	-0.9
	OSF @ 2nd Level	370	1183	1988	543	631	692	463	1053.1	930.7	-19.7	39.0	8.6
	OSF @ 3rd Level	226	921	2330.3	326	314	657	2520	937.2	1032.3	-51.0	8.2	27.3

Table 8: Summary of analysis results of each model for % load increase in walers adjacent to a failed strut at a level

Model 1: strut g at level 1 when fails/ deactivated in analysis, there is 51% load increase in the strut g at level 2 exactly below the failed strut. And on average 49% increase in load horizontally at level 1 in f and h strut. Vice-versa when the level 2 strut g fails/ made deactivated in the analysis, the % load increase in the strut g at level 1 vertically above it is 74% whereas there is nominal increase in the load of struts f and h, at level 2. The waler beams which are horizontal member along the periphery of the soil support system, has % increase in BM by 59% due to OSF at level 1 and by 96% due to OSF at level 2.

Model 2: strut b at level 1 when fails/ made deactivate in analysis, there is 78% load increase in the strut b at level 2 exactly below the failed strut and no change or a decrease in load is noted in the strut b at level 3. Horizontal struts with % load increase are in range of 20~25%.Vice-versa when the level 2 strut b fails/ made deactivated in the analysis, the % load increase of load in strut b at level 1 vertically above it is 73% and % increase of load in strut b at level 3 is 70%. In case when the strut b fails at level 3 the % increase in load at level 1 is -21% and at level 2 is 168.5%. While for 3 strut system, the % increase in waler BM was found to be approx. 40% due to OSF at level 2 for both the models Model 2 and Model 3.

Model 3: strut b at level 1 when fails/ made deactivate in analysis, there is 39% load increase in the strut b at level 2 exactly below the failed strut and no change or a decrease in load is noted in the strut b at level 3. Vice-versa when the level 2 strut b fails/ made deactivated in the analysis, the % load increase of load in strut b at level 1 vertically above it is 77% and % increase of load in strut b at level 3 is 106%. In case when the strut b fails at level 3 the % increase in load at level 1 is 0.6% and at level 2 is 53%.

7. CONCLUSION

From the above results for 3 different model system, it is observed that force redistribution (increases) vertically in the struts above or below of the failed strut is in the range of 56.6% to 78%. However, in horizontal direction i.e., at level of failed strut there is nominal % increase of range 15% to 30% in the adjacent struts.

Due to OSF condition the span of the waler in the axis of bending (major axis) becomes laterally unsupported thereby the tributary area of load increases for waler due to failure of a strut and hence the BM in waler increases. The % increase in waler BM is in the range of 20% to 60%. Whereas the impact of OSF on other level has an impact of 70% to 96%. That means the impact in magnitude of load increase in strut is less compared to waler. Since the partial safety factors for normal case is 1.5 against 1.05 for OSF case, the increase in magnitude of load can be still within the design capacity. Therefore, the OSF case shall always be examined for any temporary soil support system to rule out any catastrophic collapse and give the safe and stable robust design. From the analysis results, it can be outlined that cost implication with OSF check will not have much impact.

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