INCLINED STRUT SYSTEM IN TOP-DOWN CONSTRUCTION METHOD

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This paper presents the redesign of temporary earth supporting system used for construction of Opera House Station (OPH), the first underground metro station ever built in Vietnam.

1. INTRODUCTION

OPH is in the busiest business district of Ho Chi Minh City, and surrounded by many historical buildings (Fig. 1). Since most are shallow foundation and sensitive to adjacent construction activities, top down method is adopted by main contractor, Shimizu - Maeda Joint Operation. Diaphragm wall is designed as both temporary and permanent earth stabilizing structure with toe embedded in hard diluvium clay to ensure water tightness inside station box during construction. The wall is assisted by three to four layers of temporary inclined struts. Supported by upper permanent slabs, these struts are used instead of horizontal ones to have better working space (Fig. 2).

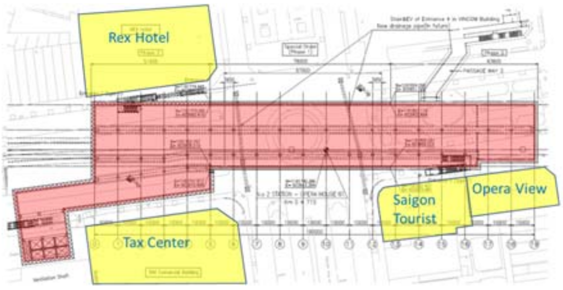

Figure 1: OPH Station Layout

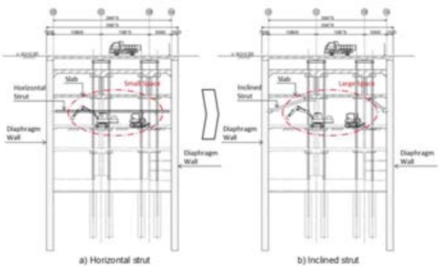

Figure 2. Redesign of Strutting System

2. INCLINED STRUT SYSTEM

Unlike conventional strut system where lateral force is the main concern, inclined struts introduce the uplift which causes radical change in design and construction of temporary works. First, to avoid excessive deformation of permanent slabs or longitudinal girders, vertical members such as permanent columns and kingposts are utilized. Second, drop panels are reinforced to receive load from the struts. Third, connection between kingposts and slabs is redesigned to accommodate the uplift. Fourth, shear connectors required to transfer load between strut and diaphragm wall make the steel walers become impracticable. Concrete walers thus are used instead. Finally, slab deformation due to uplift greatly affects stiffness of strut. Unfortunately, 1D soil-spring based earth retaining analysis software like Kasetsu-5x and Wallap is commonly unable to capture this effect directly. Therefore, it is necessary to convert complex inclined strut to equivalent horizontal spring before running analysis by software. Detail will be discussed in the next section.

3. EQUIVALENT HORIZONTAL STIFFNESS

3.1 Horizontal Displacement by Axial Compression

According to Rao et al. (1999), equivalent horizontal stiffness of a single inclined strut (Fig. 3a) and struts in series is given by Eq.1 and Eq.2 respectively.

$$k_c = k\cos^2\alpha \tag{1}$$

$$k_c = \frac{1}{\Sigma\left(\frac{1}{k_i}\right)} \tag{2}$$

Where, α is inclination angle and k_i is spring constant of each member. Substituting Eq. 1 into Eq. 2, we obtain equivalent horizontal spring constant k_c of a combined strut (Fig 3b) and its horizontal displacement Δl_c under axial compression force R.

$$k_c = \frac{1}{\Sigma\left(\frac{1}{k_i\cos^2\alpha_i}\right)} \tag{3}$$

$$\Delta l_c = \frac{R}{k_c} \tag{4}$$

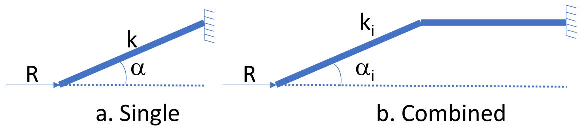

Figure 3: Inclined Strut

3.2 Horizontal Displacement by Uplift

It is assumed in section 3.1 above that vertical deformation of strutting system is small and ignorable. Uplift however induces upward deformation of slab and horizontal displacement of strut (Fig. 4). This configuration or uplift displacement is different from the displacement by axial compression discussed previously. According to The American Wood Council (2005), vertical stiffness of a fixed-fixed slab or beam k_b under point load (Fig. 5) can be obtained using Eq. 5. In fact, the system becomes stiffer with presence of kingposts and upper slabs (Fig 4). In this case, Eq. 6 to Eq. 8 are used to estimate the slab deformation y. The horizontal displacement of strut due to uplift Δl_u is then determined using Eq. 9 to Eq. 11.

$$k_b = \frac{P}{y} = \frac{3EI(a+b)^3}{a^3b^3} \tag{5}$$

$$k_v = k_b + k_p \tag{6}$$

$$y = \frac{P}{k_v} \tag{7}$$

$$P = R(cos\alpha + cos\beta) \tag{8}$$

$$\Delta l_u = \Delta l_1 + \Delta l_2 \tag{9}$$

$$\Delta l_1 = a - \sqrt{a^2 + c^2 - (c+y)^2} \tag{10}$$

Keyword: Inclined strut, Top-Down construction method, earth retaining and supporting system
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$$\Delta l_2 = b - \sqrt{b^2 + c^2 - (c+y)^2} \qquad (11)$$

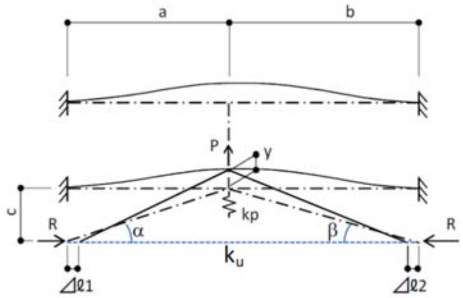


Figure 4: Uplift Shortening

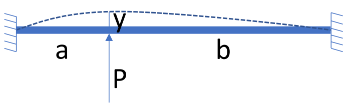


Figure 5: Fixed-fixed Support Slab under Point Load

Where, E and I: Young's modulus and moment inertia of the slab; k_p: spring constant of the kingpost which can be estimated following recommendation by JRA (2012); k_v: vertical stiffness of the kingpost and slab; a, b, c: lateral and vertical projection of struts (Fig. 4); α, β : inclination of struts; P: uplift force; R: strut force; y: slab deformation at uplift load point (Fig. 4).

So equivalent horizontal spring constant by uplift is

$$k_u = \frac{R}{\Delta l_u} \qquad (12)$$

3.3 Equivalent horizontal spring constant

Horizontal displacement of an inclined strut is sum of axial compression and uplift displacement

$$\Delta l = \Delta l_c + \Delta l_u \qquad (13)$$

Equivalent horizontal stiffness of an inclined strut is thus

$$k_{eq} = \frac{R}{\Delta l} = \frac{R}{\Delta l_c + \Delta l_u} = \frac{1}{\Delta l_c/_R + \Delta l_u/_R} \qquad (14)$$

Substituting Eq. 4 and Eq. 12 into Eq. 14, we get

$$k_{eq} = \frac{1}{1/_{k_c} + 1/_{k_u}} \qquad (15)$$

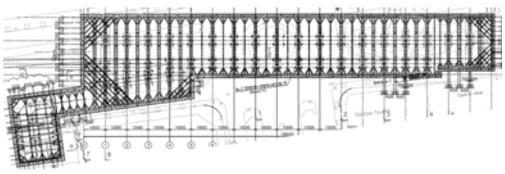
Estimation of vertical displacement of slab y requires strut load R which in turn depends on equivalent horizontal stiffness k_{eq}. Some iterations (usually 2 to 3) are required to get final k_{eq} or R with acceptable tolerance. It is advisable to start with $k_{eq} = k_c$. Table 1 below illustrates a simple calculation example for the system in Fig. 4 with strut load R assumed to be 1000kN/m. Equivalent horizontal stiffness k_{eq} of the inclined strut is about 74.5% of its axial compression stiffness k_c. In other words, uplift deformation decreases the stiffness of the inclined strut by 25.5%. The reduction would be much greater without kingpost as its stiffness k_p is 4.2 times greater than slab's one k_b. This confirms the significant contribution of kingpost.

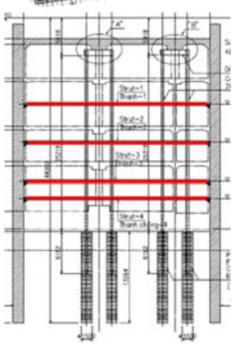
Table 1. Example of Equivalent Stiffness

ΣEI_i (kNm^2/m)	a (m)	b (m)	c (m)	R (kN/m)
2343750	10.8	12.875	3.514	1000
k_c (kN/m/m)	k_b (kN/m/m)	k_p (kN/m/m)	k_u (kN/m/m)	k_{eq} (kN/m/m)
314412	30849	129900	919149	234274

4. RESULT AND CONCLUSION

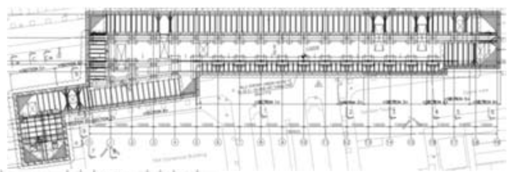
Fig. 6 below shows earth retaining structure before and after redesign. The inclined system not only increases working space but also reduces cost for temporary works by around 60%. The major disadvantages are heavier design workload, more complicated concrete works as well as additional temporary posts required between permanent columns. Overall, the benefits from the redesign of temporary works outweigh the its drawbacks.

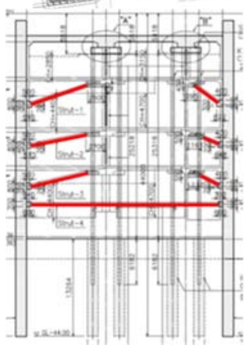




1. Horizontal struts
2. Steel walers
3. Simple drop panels
4. No temporary posts

a. Original Design – Horizontal Strut System





1. Inclined struts
2. Concrete walers
3. Complicated drop panels
4. Temporary posts required

b. Final Design – Inclined Strut System

Figure 6: Earth Retaining Support System - Before and After Redesign

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