

EFFECT OF NOSE BLADE ANGLE ON FACE STABILITY OF JACKED BOX TUNNELLING

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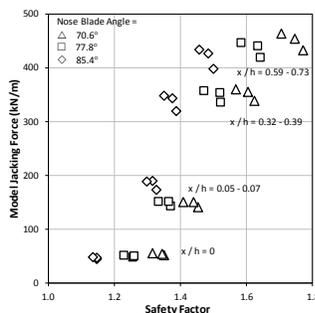
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Graphical abstract



Abstract

A typical jacked box tunnel usually consists of a precast concrete box tunnel and a steel nose blade installed in the box front. Two of many design factors for this tunnel type are the face stability and the face resistance; an increase in face stability is typically accompanied by an unintended consequence of an increase in face resistance. A series of numerical analyses was performed to explore the interaction between the face stability and the face resistance. Three design parameters were considered, namely amount of unexcavated soil inside box tunnel, nose blade angle and soil depth. Plane strain finite element models were used to simulate the tunnel jacking process; the software used was Plaxis 2D. The face stability represented by safety factor is affected mainly in a decreasing order by the amount of unexcavated soil inside box tunnel and the nose blade angle. However, if a minimum jacking force is required, an optimal combination of the two design parameters should be adopted.

Keywords: Box jacking; unexcavated soil; nose blade angle; face stability; jacking force

Abstrak

Sebuah terowong kekotak terbucu terdiri daripada terowong kekotak pra tuang konkrit dan bilah muncung keluli yang dipasang di bahagian hadapan kotak. Dua daripada banyak faktor rekabentuk ialah kestabilan muka dan ketahanan muka terowong; peningkatan kestabilan pada kestabilan muka umumnya disertai dengan kenaikan ketahanan muka terowong. Siri analisis berangka telah dilakukan untuk meneliti interaksi antara kestabilan muka dan ketahanan muka terowong. Tiga parameter rekabentuk yang diteliti adalah jisim tanah tidak tergali di bahagian dalam terowong, sudut bilah muncung, dan kedalaman tanah. Model elemen terhingga terikan satah telah digunakan untuk mensimulasi proses pembicuan terowong; perisian yang digunakan adalah Plaxis 2D. Kestabilan muka yang diwakili oleh faktor keselamatan paling utama dipengaruhi oleh jisim tanah tidak tergali diikuti dengan sudut bilah muncung. Namun, jika perlu mendapatkan daya bicu minimum, kombinasi optimal dari dua parameter rekabentuk tersebut perlu diterima pakai.

Kata kunci: Kotak bicu; tanah tak terkorek; sudut bilah muncung; kestabilan muka; daya bicu

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1.0 INTRODUCTION

Jacked box tunnelling is a suitable method for constructing a new shallow crossing roadway underneath a very busy roadway. By using this method, the tunnel construction does not interfere with that very

busy roadway. Concrete box segments are jacked by a series of hydraulic jacks, and a steel nose blade is installed in the front segment to protect the box tunnel during the jacking process. The soil mass inside the box tunnel due to nose blade penetration is then excavated continuously. However, analysis and design

aspects of this method are not widely discussed in literature; Komiya and Nakayama [1] discuss the finite element analysis of a 30 m long box tunnel jacking considering its construction sequences. More literature discusses the construction aspects of jacked box tunnelling. Nozawa [2] discusses briefly the rapid element pull method and the jointed element structural method. Allenby and Ropkins [3] discuss a certain technology for jacked box tunnelling. Hung *et al.* [4] summarizes mainly the US jacked box tunnelling experience of Interstate I-90 for the Central Artery/Tunnel (CA/T) Project.

The research for this paper was developed based on the recent experience concerning a 93 m long concrete box tunnel jacked underneath a Jakarta-Bogor toll-way to provide an additional roadway for the crossing local traffic; more details of the project were reported by Prakoso and Lase [5]. During the construction, to increase the stability of soils in front of the nose blade or face stability, the amount of unexcavated soil inside the box tunnel was rather significant. However, as reported in [5], a greater amount of unexcavated soils led to an unintended, greater required jacking force. Furthermore, they report that a greater amount of unexcavated soils led to greater ground surface deformation.

This paper assesses influencing factors for the face stability, including amount of unexcavated soil inside box tunnel, and nose blade angle, and soil depth. The box tunnel outer cross-sectional dimensions were 9.7 m in width and 7.4 m in height as shown in Figure 1. The box tunnel wall thickness is 600 mm. The length of top nose blade was 2.55 m (=1.60 m pointing part + 0.95 m flat part), while the length of bottom nose blade was 1.95 m (=1.00 m pointing part + 0.95 m flat part). An anti-drag system was installed around the concrete box tunnel during jacking to reduce the required jacking force. The associated relation to the face resistance is also briefly evaluated. Based on these results, design recommendations are subsequently proposed.

2.0 NUMERICAL ANALYSIS

2.1 Basic Concept

When jacked laterally into a soil mass, a box tunnel would encounter several resistances, namely the top and bottom shear resistances, the right and left side shear resistances, and the face resistance. In a two-dimensional analysis, the right and left shear resistances are not considered, and as shown in Figure 2, only the top and bottom shear resistances and the face resistance are considered. The face resistance therefore is the summation of a) the volumetric soil resistance and b) the friction and adhesion between the tunnel inner wall and the soil due to the penetration of the top and bottom nose blades. The box tunnel depth and the amount of unexcavated soil in box tunnel would theoretically affect the face resistance.

The top and bottom shear resistances are directly affected by the anti-drag system used.

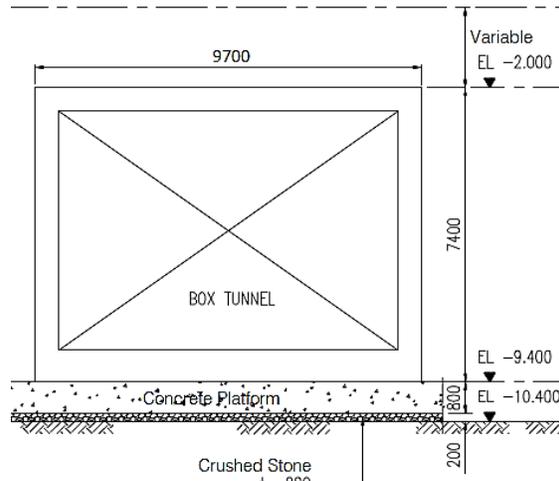


Figure 1 Force diagram during jacking

The numerical analyses are performed by applying a horizontal prescribed displacement, simulating the actual jacking process. The required jacking force is then registered at the end of jacking process. The top and bottom shear resistances are calculated from the respective interface elements between the tunnel wall and the soil. Therefore, the face resistance is determined by the following:

$$\text{Face Resistance} = \text{Jacking Force} - (\text{Top Shear} + \text{Bottom Shear}) \quad (1)$$

The face resistance can be normalized by the following:

$$N^* = \text{Face Resistance} / (c \times H) \quad (2)$$

in which c = soil cohesion and H = height of box tunnel.

The stability of the soil mass in the front area of the jacked box tunnel as shown in Figure 3 is subsequently analysed. The output considered is the safety factor.

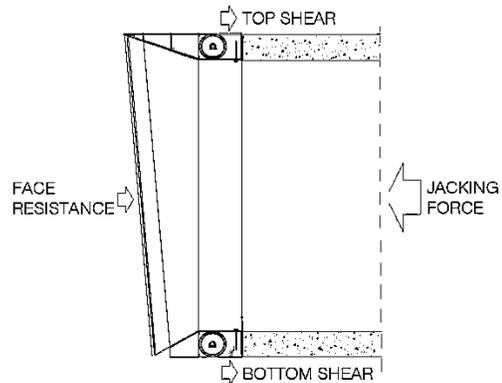


Figure 2 Forces during jacking process

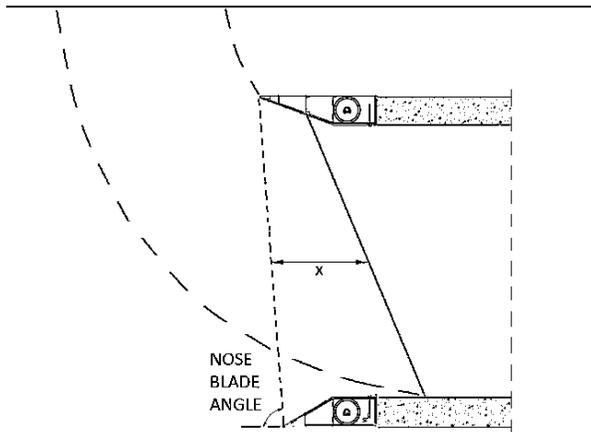


Figure 3 Box tunnel face stability

2.2 Numerical Modelling

Plane strain finite element models in Plaxis 2D [6] was developed to simulate the tunnel jacking process. Fifteen-node triangular elements were used for the soil mass, concrete box tunnel walls and steel nose blades; the typical finite element mesh is shown in Figure 4. As summarized in Table 1, the soils were assumed to follow the Mohr-Coulomb model, while the concrete box tunnel walls and steel nose blade were assumed to be elastic. The strength of soil-box tunnel interface elements was only 10 percent of that of the soil to model the anti-drag system. Although it is actually made of steel structure (WF section steel ribs and covering steel plates), the nose blade was assumed as a solid material with low, equivalent property values. To ensure the rigidity of the box tunnel, dummy rigid vertical truss elements (thick, solid lines inside the jacked box in Figure 4) were used to connect the tunnel top and bottom walls.

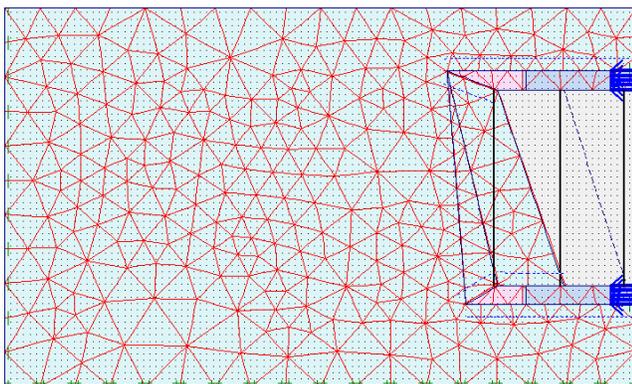


Figure 4 Typical finite element mesh

The models assume a displacement controlled jacking condition, employing the prescribed displacement option in Plaxis 2D [6]. The 0.1 m

prescribed displacement was applied to the right side of the box tunnel top and bottom walls (horizontal arrows on right side of mesh shown in Figure 4); to allow the application of prescribed displacement, no fixities were used on the wall right side, and two additional soil nodes with horizontal fixity were placed 0.1 m above the top wall and below the bottom wall. Details of the modelling procedure for this prescribed displacement can be found in [5]. Following the phase of jacking process, an analysis using the $c-\phi$ reduction procedure was conducted to obtain the safety factor of the face stability. The observed outputs are the required jacking force and the safety factor.

2.3 Cases

The cases considered in this paper comprised those with different amounts of unexcavated soil inside box tunnel, nose blade angles, and soil depths. Different amounts of unexcavated soil inside the box tunnel were also considered to simulate the actual jacking conditions described discussed in [5]. The representing parameter for the first design parameter was the distance from the front imaginary soil line to the actual soil surface inside the box tunnel at the box tunnel middle height. Three basic distance variations were considered: 0.40 m – 0.45 m, 2.35 m – 2.85 m, and 4.40 – 5.40 m, as shown in Figure 5. The distance was subsequently normalized by the box tunnel height. It is noted that the reduction factor for the friction and adhesion of the tunnel inner walls was the same as that of the outer walls.

The nose blade angle was varied by changing the length of the flat part of the top nose blade. It is noted that the nose blade angle is defined as the angle between the line connecting blade top and bottom tips and the horizontal plane. Three lengths were considered 0.95 m, 1.95 m, and 2.95 m, resulting in the nose blade angles of 85.4°, 77.8°, and 70.6°, respectively, as shown in Figure 5. The actual design length was 0.95 m [5]. In addition, the soil depths (from ground surface to tunnel top) were 2.0 m, 2.5 m and 3.0 m.

Table 1 Model material properties

Properties	Soil	Concrete	Nose Blade
γ (kN/m ³)	17	24	10
E (MPa)	35	20,000	5,000
ν	0.35	0.2	0.35
ϕ (°)	10	-	-
c (kPa)	28	-	-
Interface	0.1	-	-

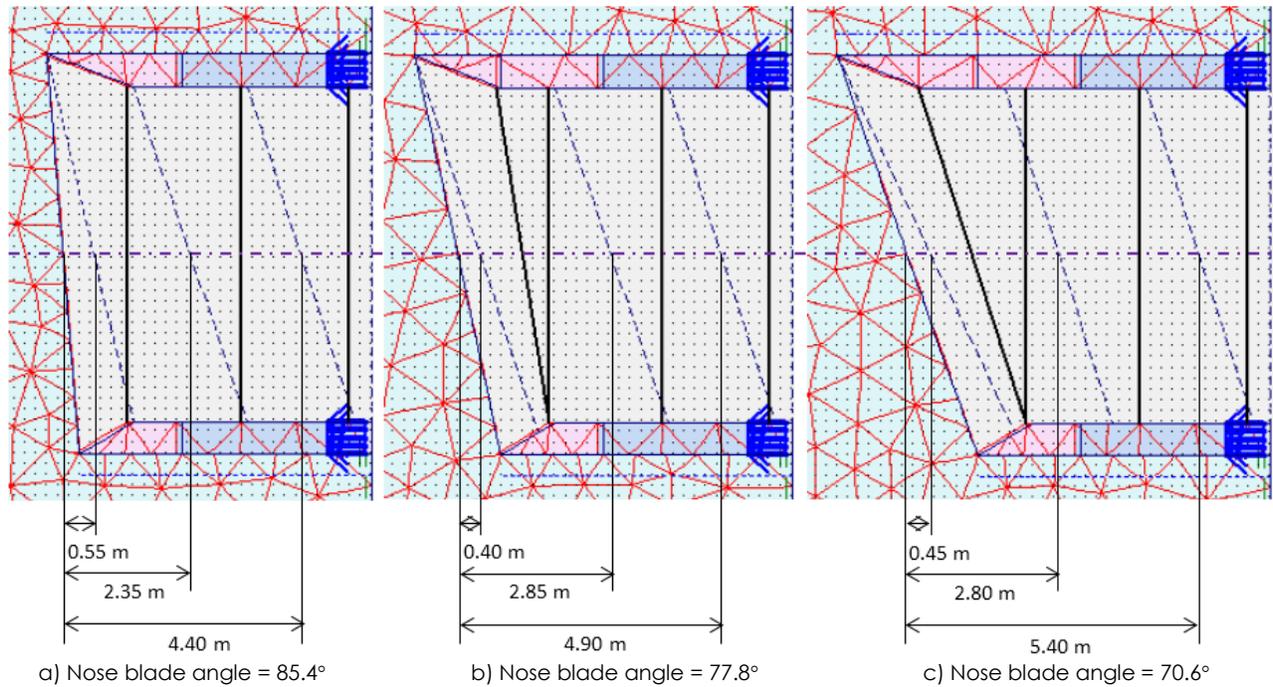


Figure 5 Variation amount of the unexcavated soil and nose blade angle

3.0 RESULTS AND DISCUSSION

The soil mass displacement contours after the $c-\phi$ reduction procedure for cases with amount of unexcavated soil $x/h = 0$ and $x/h = 0.66$ (nose blade angle = 77.8°) are shown in Figure 6. The safety factors obtained for $x/H = 0$ and $x/H = 0.66$ are 1.256 and 1.641, respectively. The lower safety factor can be associated with the shorter failure surface. The greater safety factor appears to be provided by the shearing of the unexcavated soil inside the box tunnel. In addition, analyses with a lower interface factor of 0.001 resulted in slightly lower safety factors (only up to safety factor difference of 0.05), suggesting a complex shearing mechanism within the soil inside box tunnel.

The contours for nose blade angles of 70.6° and 85.4° ($x/H = 0$) are shown in Figure 7. The safety factors for both angles are 1.350 and 1.147, respectively. The lower safety factor can be associated with the steeper and therefore shorter failure surface. The lower nose blade angle appears to push the failure surface farther away from the nose blade, creating a gentler and therefore a longer failure surface. It can be observed from the comparison of Figures 6 and 7 that the level of change in the safety factor can be associated with the level of change in the length of failure surface.

The effects of the amount of unexcavated soil inside the box tunnel and the nose blade angle are examined further, as shown in Figure 8. In general, the safety factor decreased with an increased in nose blade angle or a steeper blade angle. However, the safety factor increased with an increased in amount

of excavated soil. The increased in safety factor due to a gentler angle is in the order of 0.13 to 0.27, while the increased due a greater amount of unexcavated soil is in the order of 0.35 to 0.42.

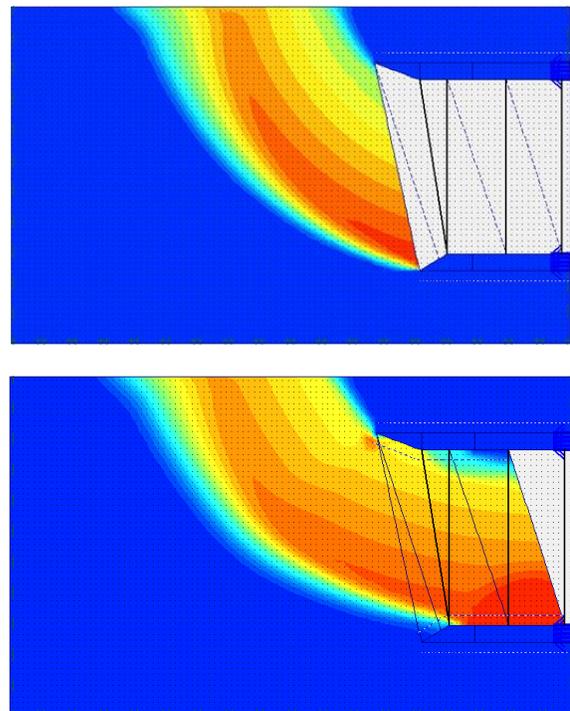


Figure 6 Soil mass displacement contours for different amounts of unexcavated soil (nose blade angle = 77.8°)

The effect of the soil depth is also examined, as shown in Figure 9. In general, the safety factor does not change significantly with an increase in soil depth. The change in safety factor is just in the order of less than 0.05.

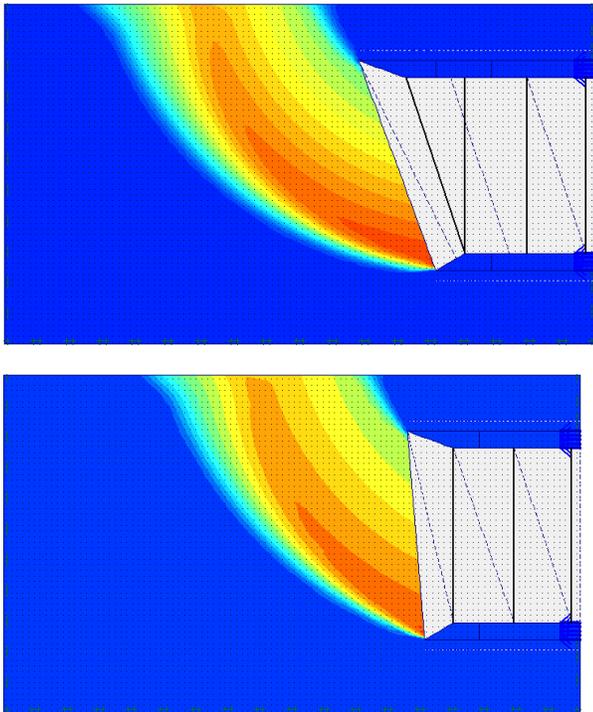


Figure 7 Soil mass displacement contours for different nose blade angles ($x/H = 0$)

The safety factor was examined further by comparing it against the model jacking force, as shown in Figure 10. It is noted that it is desirable to have a minimum jacking force to minimize the required number and capacity of hydraulic jacks, as well as the required jacking reaction capacity. In general, the model jacking force increases with an increase in safety factor. The summation of top and bottom shear resistances remained practically the same for different cases considered, indicating the increase in model jacking force was primarily due to the increase in the face resistance; further discussions on the face resistance can be found elsewhere [7]. Furthermore, for a given nose blade angle, the jacking force increased significantly with an increased in the amount of excavated soil inside box tunnel (from about 50 kN/m for $x/H = 0$ to about 450 kN/m for $x/H = 0.59 - 0.73$). For a given amount of unexcavated soil inside the box tunnel, the jacking force is practically independent of the nose blade angle. In addition, as suggested by clusters of three soil depths, the jacking force is also practically independent of the soil depth.

The relationship in Figure 10 suggests a design approach for maintaining the face stability during jacking. A combination of nose blade angle and amount of unexcavated soil appears to be more promising to balance the safety factor and the

required jacking forced, compared to just an individual design parameter (e.g., either nose blade angle or amount of unexcavated soil). For example, for a prescribed safety factor of 1.5, the combination of nose blade angle of 77.8° and amount of unexcavated soil $x/h = 0.32 - 0.39$ is more desirable compared to the combination of nose blade angle of 85.4° and amount of unexcavated soil $x/h = 0.59 - 0.73$, because the former would require a less jacking force (about 350 kN/m versus about 430 kN/m in Figure 10). A further analysis might reveal a more optimal combination; as can be interpolated from the relationship in Figure 10, a nose blade angle of 70.6° and an x/H of about 0.20 might resulted in a safety factor of about 1.5 and less, required jacking force of about 250 kN/m.

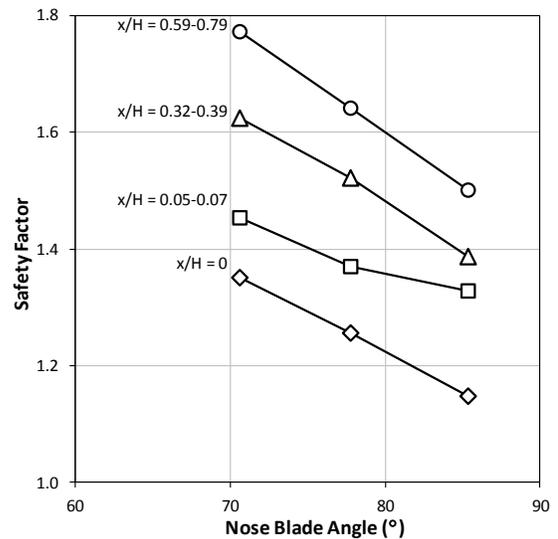


Figure 8 Effects of amounts of excavated soil and nose blade angles on safety factor

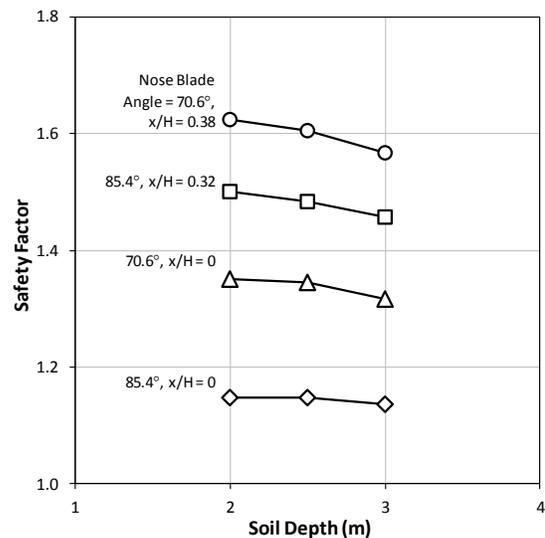


Figure 9 Effect of soil depth on safety factor

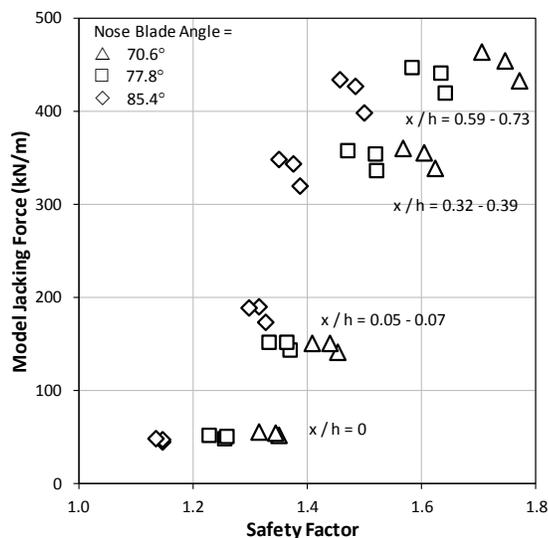


Figure 10 Relationship between model jacking force and safety factor

4.0 CONCLUSION

Two design factors in jacked box tunnelling, namely the face stability (represented by safety factor) and the face resistance (represented by model jacking force) were examined through a series of plane strain finite element analyses. The considered design parameters were the amount of unexcavated soil inside box tunnel, the nose blade angle and the soil depth. For each case, a two-step analysis was performed; the first step was the simulation of the displacement controlled jacking process, and the second step was the stability analysis. The observed outputs were the required jacking force and the safety factor.

The general conclusion of this study was that the safety factor increased with an increased in the amount of unexcavated soil inside box tunnel, as well as by the nose blade angle. The safety factor was practically independent of the soil depth. Furthermore, the soil mass displacement contours suggested that the increase in safety factor could be associated with a longer failure surface.

The safety factor was examined further by comparing it against the model jacking force. In general, the jacking force increased with an increased in safety factor. For a given nose blade angle, the jacking force increased significantly with an increased in the amount of excavated soil inside box tunnel. For a given amount of unexcavated soil inside the box tunnel, the jacking force was practically independent of the nose blade angle and of the soil depth. The jacking force – safety factor relationship suggested that a combination of nose blade angle

and amount of unexcavated soil appears to be the promising approach to balance the safety factor and the required jacking force.

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