A Study of Cuttability Indices for Tunnel Penetration

Étude sur les indices d’aptitude à la coupe pour la pénétration de tunnels

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ABSTRACT: To speed up construction of mass transit subway and the popularity rate of sewage, Taiwan's underground excavation works, especially for mechanical cutting cases, show an ascendant tendency. This study presents a generalized solution for underground geological-mechanical interaction. By using dimensional analysis, this model generalizes geological characteristics grouped into three categories: (1) brittle (rock-like), (2) the ductile (soil-like), and (3) brittle-ductile (gravel-like) type with respect to two cutting forces: (1) thrust and (2) torque to evaluate their excavation/penetration rate. Furthermore, the leading cuttability indices can be obtained to enable to assess the underground excavation. Meanwhile, in-situ experimental results from shield tunneling and pipe jacking construction were used to examine this model and it showed a nice agreement between both. From this analytical approach, a proposed “oval-shaped cutting ellipsoid”, including its center (O), area (A), and long/short axis (ax/by, or ay/bx), can be used not only to estimate the functionality and efficiency of cutting machine adopted for tunnel project, but also to offer a warning information for inadequate cutting strategy.

RÉSUMÉ: Pour accélérer la construction du système de transport en commun souterrain et des eaux usées, les travaux d'excavation souterrains de Taïwan, en particulier les coupes mécaniques, montrent une tendance ascendante. Cette étude présente une solution généralisée pour l’interaction géologique-mécanique souterraine. En utilisant l'analyse dimensionnelle, ce modèle généralise les caractéristiques géologiques regroupées en trois catégories: (1) fragile (comme la roche), (2) l'ductile (comme le sol), et (3) fragile-ductile (comme le gravier) en respectant deux types de coupe: (1) la poussée et (2) torsion pour évaluer leur taux d’excavation / pénétration. Par ailleurs, les indexes d’aptitude à la coupe peuvent être obtenue pour permettre d'évaluer l'excavation souterraine. Pendant ce temps, les résultats expérimentaux in-situ de bouclier tunnel et de la construction de tuyau de fonçage ont été utilisés pour examiner ce modèle et ceux-ci concordent. A partir de cette approche analytique, une proposition de «ellipsoïde de coupe de forme ovale " (comprenant son centre (O), sa surface (A) et ses axes longs et courts (ax/by, ou ay/ bx)) peut être utilisé non seulement pour estimer le bon fonctionnement et l'efficacité de la machine de découpage adopté pour le projet de tunnel, mais aussi pour fournir une alerte à propos d’une stratégie de coupe inadaptée.

KEYWORDS: Generalized cutting mechanism , Thrust, Pipe jacking, Cuttability indices

1 INTRODUCTION

1.1 *Multi-scale underground cutting project*

Recently, the construction projects increase the cases of underground tunneling by mechanical cutting such as tunnel in the mountain, mass rapid transportation system in the city and sewer system, etc. There are different types of cutting methods including TBM, shield tunnel (ST), as well as pipe jacking (PJ) with various sizes corresponding to different geological conditions (see Figure 1). This study presents a normalized evaluation to meet the multi-scale underground cutting projects so that all of the in-situ data can be collected and compared with each other.

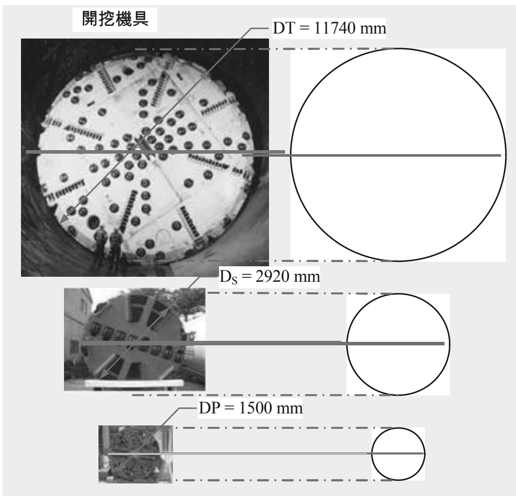

Figure 1. Different size of cutting machines ranged from 11740 to 1500 mm in diameter.

2 CONCEPTUAL MODEL

2.1 *Indentation-typed fracture mechanism*

Based upon normal indentation fracture in a Mohr-Coulomb material, Huang (2000) proposed a conceptual model as follows:

$$(1+\mu)\xi^{*(k_d+1)/k_d} - \mu\xi^{*(k_p+1)/k_p} = \gamma \qquad (1)$$

where γ is a key dimensionless factor, which is a function of wedge angle of cutter , elastic constants and plastic strength parameters.

$$\xi_* = \xi_*\left(E, \upsilon\left(or\ G\right), q_u, \phi, \phi^*, \beta_i, \sigma_c\right) \qquad (2)$$

and ξ is defined as dimensionless elasto-plastic (E-P) radius while ξ* reach critical value where brittle fracture occurs on this E-P interface. Thrust force, therefore, can be estimated using the indentation pressure P and indentation force F as seen in Figure 2 schematically.

$$\frac{P}{q} = \frac{1}{K_p - 1}\left\{\frac{(n+1)\cdot K_p}{K_p + n}\cdot \xi_*^{n\cdot(K_p-1)/K_p}\cdot -1\right\} \qquad (3)$$

$$F_i = (3-n)\cdot \pi^{n-1}\cdot P\left(\frac{d}{\tan\beta}\right) \qquad (4)$$

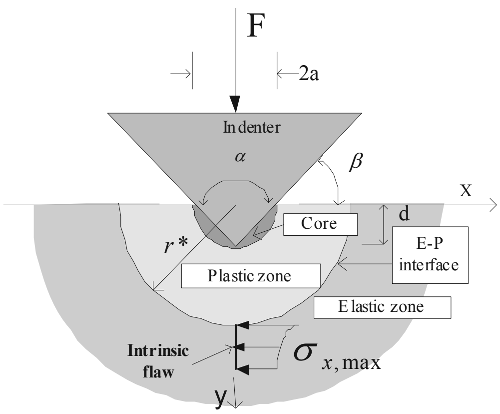

Figure 2. Schematic normal indentation fracture

2.2 *Generalized trust system*

This study presents a generalized trust system of cutter head globally by taking each different types of individual cutters into account locally with respect to different methods (TBM, ST, and PJ) and geological conditions (rock, soil, & gravel). Figure 3a and 3b show the total trust force F, which is consists of front resistance F_f and lateral resistances F_p including both $F_{p,m}$ for machine itself and Fp,p for pipes.

$$F = F_f + F_{p,m} + F_{p,p} \qquad (5)$$

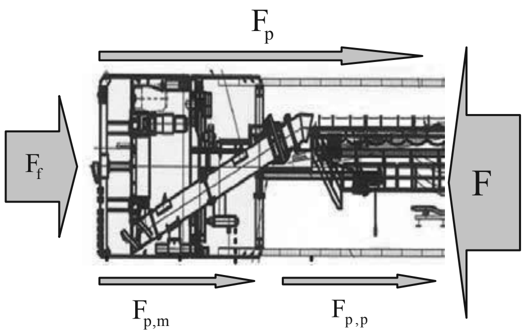

Figure 3a. Trust force system

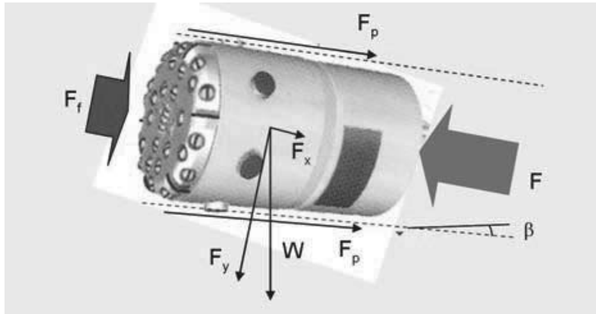

Figure 3b. Trust force system with inclined angle

Therefore, Ff (kN) is estimated from different types (nj) of cutters fj and water/earth pressure Ps (kN/m2):

$$F_f = \sum_{j=1}^{m} n_j \cdot f_j + P_s \cdot A \qquad (6)$$

where A is cross area of cutter head (m^2).

This paper presents an analytical estimation to deal with different mechanical cutting methods (tunnel boring machine, shield tunnel and pipe jacking), construction types (earth pressure balance, slurry pressure balance, thick-mud), and geological conditions (soil, gravel and rock) by generalizing their total thrust system. The straight-line thrust is calculated for either wedge- or conical-typed cutters of tunneling machine. In this generalized work, the upper bound and lower bound of trust are highlighted for the warning situations for risk assessment.

3 CASE STUDY

3.1 *Case I: Taoyuan tunneling project in Taiwan*

In addition, the in-situ data of trust in shield machine (Taoyuan tunneling project) is presented to confirm with. It depicts a favorable agreement for the estimation of thrust in this study as shown in Figure 4 (cutter head), and Figure 5 (results) with respect to normal cutting as well as abnormal conditions (point a and b shown in Fig.5) once the in-situ data out of the theoretical boundaries.

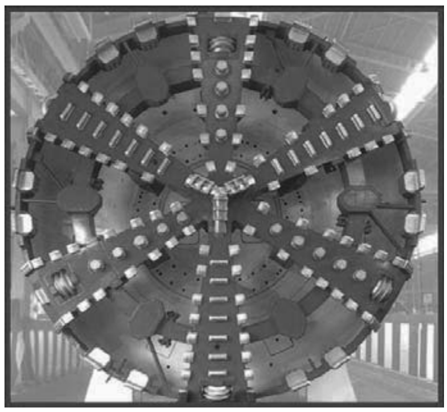

Figure 4. Cutting head in field for shield tunnel project

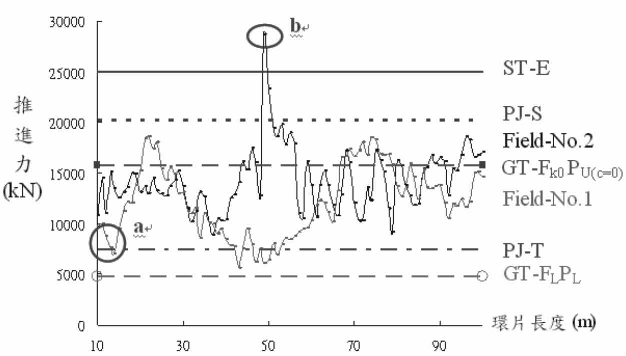

Figure 5. Theoretical upper and lower bounds associated with data curve in field for shield tunnel project (vertical axis: trust in kN and horizontal axis: rate of penetration in m)

3.2 *Case II: Pipe jacking project in Taiwan*

Another case study is presented for pipe jecking tunnel shown in Fig. 6.

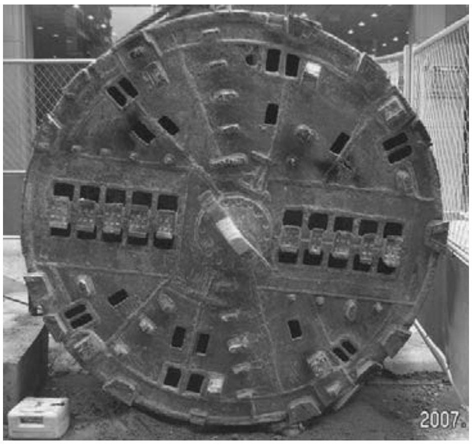

Figure 6. Cutting head in field for pipe jacking project

Unlike a flat data curve in field for the case of shield tunnel, the in-situ data curve for pipe jacking method in Fig. 7 increases in trust (vertical axis) with the increase of rate of penetration (horizontal axis) due to the lateral resistance is proportional to the pipe length. In this cutting case of sewer system, there is no abnormal excavation situation such that the data curve does not reach the theoretical boundaries.

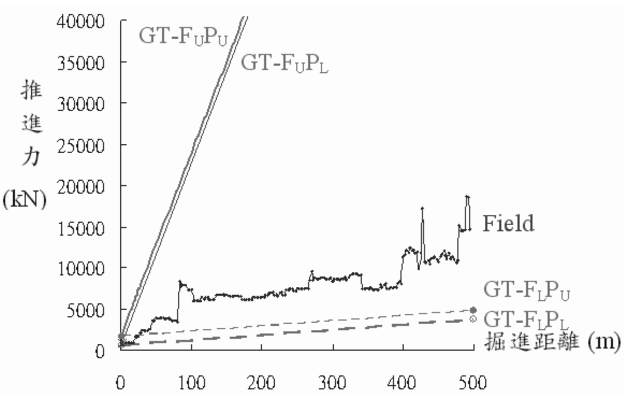

Figure 7. Theoretical upper and lower bounds with in-situ data curve for pipe jacking project of sewer system (vertical axis: trust in kN and horizontal axis: rate of penetration in m)

4 CONCLUSIONS

The results shows that the total thrust for upper bounds and lower bounds are: (401%, 37.8%) and (258.2%, 31.7%) compared with normal condition in gravel and weathered sandstone cases respectively, which normalized boundary values are (13×10-4 ~ 82×10-4) and (0.97 ~ 4.98) for cutting-head resistance respectively. It also found that the cutting-head resistance take about 28% of the total trust resistance (F=4773kN) in the gravel case by taking cutters' forces into account.

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