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論文題名：DEVELOPMENT OF JACKING FORCE PREDICTION METHOD FOR BOX PIPE-JACKING SYSTEM BY USING MACHING LEARNING（矩形推進工法における機械学習を用いた推進力予測法の開発）

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論　文　内　容　の　要　旨

Box-jacking as a tunnelling method has gained popularity in recent years for locating underground utilities and infrastructure. Nevertheless, the employment of this technique still poses challenges, particularly in predicting the jacking force of long drives. Accurate prediction of jacking force is highly desirable for anomaly detection, avoiding thrust overload limits, and protecting the box culverts and launch shafts from damage. However, such a prediction entails accounting for numerous factors, including site geology, lubricated overcut, work stoppages, deviations in alignment, and the driving style of the tunnel boring machine. This study aims to identify the mechanisms by which tunneling parameters influence the development of jacking forces, with the goal of establishing a machine learning model for jacking force prediction.

The findings from this research work are included in the following chapters:

Chapter 1: This chapter introduced rectangular box-jacking technology and its associated construction methods. Rectangular box-jacking is a critical technique in the construction of underground passages and utilities, enabling the installation of large, rectangular conduits with minimal surface disruption. Additionally, this chapter outlined the motivation for this study, emphasizing three key aspects. First, it highlighted the significance of predicting jacking force, which is crucial for the safe and efficient execution of box-jacking projects. Accurate prediction of jacking force helps in preventing equipment overloads and potential structural failures. Second, the chapter delved into the mechanisms that govern jacking force, exploring how factors such as soil type, lubrication, and box geometry influence the forces involved. Understanding these mechanisms is fundamental to improving prediction models and enhancing overall project outcomes. Third, the potential for applying machine learning in the pipe-jacking industry was discussed. Machine learning offers innovative solutions for handling the complexity and variability of geotechnical data, leading to more precise and reliable predictions of jacking force. By leveraging advanced algorithms and data analysis techniques, machine learning can significantly enhance the predictive accuracy and operational efficiency of box-jacking projects.

Chapter 2: Before performing the research, a review of previous work was conducted. These works encompassed studies on interface friction, box-lubricant-soil interaction, TBM operating parameters, jacking force prediction and machine learning applications in microtunnelling, all of which were summarized in this chapter. It was found that most existing predictive models for jacking forces were developed for circular microtunnels, and their applicability to rectangular box-jacking is limited. Although some friction resistance prediction models were based on box-jacking projects, they are often specific to on-site geology and construction conditions, making widespread adoption challenging. Machine learning research on microtunnelling was also reviewed in this chapter. However, only a small number of scholars have utilized machine learning for jacking force prediction in pipe-jacking. Additionally, most existing machine learning research focuses on individual projects, often lacking the capacity for generalization. This presents a significant opportunity to utilize advancements in machine learning to enhance jacking force prediction models related to rectangular box-jacking.

Chapter 3: This chapter introduced and described two box-jacking case histories completed in the Greater Tokyo Area of Japan: a 150-m drive in sands (Tsujido Project), and a 220 m drive in silt and sands (Ougi-dori Project). For each case history, relevant project details were provided including geotechnical information, construction specifics, lubrication details, pipeline depth, box culvert details, and jacking records. Additionally, this chapter also provided the interpretation of the jacking records obtained by the TBM during jacking process, which included jacking force, cutter wheel torque, jacking speed, deviation in line, and stoppages. The interpretation of jacking records indicated that detailed monitoring of construction sites is of paramount importance, as it can reveal significant differences in driving style and tunneling characteristics as the TBM passes through different soils. When the TBM encounters harder soil, operators often adjust the cutterhead torque and penetration velocity, which can influence the development of face pressure. Additionally, it was found that frictional resistance between the box and soil often contributes most to the total jacking force during long drives. Varied geological conditions can lead to different states of contact between the box and soil. The jacking force peak caused by work stoppages cannot be ignored. An increase in skin friction after stoppages

correlates positively with the jacked distance, suggesting it may be a frictional phenomenon. This increase in frictional resistance is also influenced by the duration of stoppages and the size of the box cross-section. However, during prolonged stoppages, such as the five-day new year holiday observed in the Ougi-dori Project after a jacked distance of 175 m, the jacking force showed a downward trend upon resuming the jacking process. This may be due to changes in earth pressure at the top of the box, resulting from the continuous dissipation of lubricant pressure in the overcut during the holiday, which was detailed in Chapter 4.

Chapter 4: This chapter introduced a predictive model for calculating jacking forces, taking into account lubricant injection. Existing jacking force prediction methods for box-jacking vary in performance, with a majority of them tending to overestimate. Additionally, existing box-lubricant-soil contact model, established based on experiences and cases of circular pipe-jacking, cannot be directly applied to box-jacking. To enhance prediction accuracy, a new contact model considering lubricant injection and dissipation was proposed. This model was based on modified Terzaghi's Arching Theory for vertical earth pressure calculation and compares it with the current PBK method used in industry. The results indicated that the PBK formula effectively predicted friction resistance, thereby affirming the validity of the contact model developed in this study. It was found that, the box string is lifted and sunk during the process of lubricant injection and dissipation, causing changes in the earth pressure acting on the top of the box. Taking the Ougi-dori Project as an example, during the new year holiday, the lubricant continued to dissipate. Although lubricant injection resumed after the holiday, the injection pressure and volume in the annulus clearance were difficult to restore to previous levels in a short time. This resulted in the tendency of the soil overlaying the box to move toward the box roof, causing positive soil arching and the vertical earth pressure to reach its lower limit. Conversely, during the normal jacking process, the injection pressure in the annulus clearance was maintained at a relatively high level. Sufficient injection formed an intact mud screen around the box, preventing the lubricant in the annulus from being carried away by groundwater. This increased pressure on the outer wall of the box and caused the supporting soil layer to push upwards, resulting in negative soil arching. In this circumstance, the soil within the silo tended to slide upward, but its movement was restrained by friction in the shearing band, causing the earth pressure to reach its upper limit. However, the PBK model cannot account for the disturbance of the surrounding soil caused by lubricant injection and dissipation during the jacking process, which may result in computational errors in estimating the actual earth pressure. Consequently, the PBK model exhibited lower accuracy in predicting changes in frictional resistance induced by lubricant injection and dissipation compared to the prediction model, which incorporates positive and negative soil arching effects. Additionally, the calculation results indicated that the additional friction generated in the curved section has minimal impact on the calculated total friction value. Hence, it can be concluded that curve segments with a curvature radius exceeding 100 meters can be approximated as linear jacking, with the additional friction disregarded.

Chapter 5: This chapter presented a Bayesian updating framework for the prediction of jacking forces during box-jacking. The proposed approach was applied to the two box-jacking case histories presented in Chapter 3. Based on the analysis of the deterministic prediction model established in Chapter 4, the key (uncertain) model input parameters used for predicting jacking force during microtunnelling were identified. To benchmark the Bayesian predictions, a classical optimization technique, namely particle swarm optimization, was employed. The relative merits of both approaches were identified by comparing their results. To enhance the adaptability of the Bayesian framework to projects experiencing significant fluctuations in jacking force development—such as those resulting from long stoppages, water leakages, and alterations in geotechnical conditions—the sliding window technique was implemented. The results indicated that the Bayesian update method is effective in updating model input parameters, providing a smooth updating process for each parameter. In contrast, parameters optimized using the PSO algorithm exhibited significant fluctuations. When engineering geological conditions are stable—indicated by a stable gradient of jacking force within the foreseeable range—the Bayesian updating approach with all available jacking force data has proven highly effective. As more data were acquired from the drive, there were obvious improvements in both the mean predictions of the total jacking force and the posterior distribution of θ. The MCMC predictions of the 90% confidence interval are significant, as the data structure, particularly peaks induced by stoppages in jacking force, can be accurately captured. However, for projects characterized by complex engineering geological conditions, this study suggests incorporating the sliding window approach into the Bayesian updating process to enhance prediction performance. For example, in the Ougi-dori Project, fluctuations in jacking force were observed within a jacked distance of 100–180 meters, and the use of the sliding window approach demonstrated improved performance in reducing prediction errors. In such cases, employing all existing jacking force data for updates in the MCMC approach may capture trends from 'outdated' data, leading to significant errors in predictions for subsequent drives. Finally, a step-by-step guide for using the proposed machine learning model to predict jacking forces was presented.

Chapter 6: This chapter concluded with the results of this thesis and provides recommendations for further study.