JIPM

ISSN: 2599-1086 | e-ISSN: 2656-1778 | Vol. 7 | No. 2 | DOI: 10.35166/jipm.v7i2.58

Using Geodetic Methods in Road Construction Planning: To What Extent Will It Be Effective?

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ABSTRACT

Sustainable development is a well-known concept that is widely applied nowadays. One of the applications of this concept is through an effective planning process, such as road construction planning. Cut and fill volume measurement is an integral part of such a process, which utilizes several geodetic methods. The most commonly used instruments are waterpass and electronic theodolite (total station), but there are significant differences in their concepts. Different observation methods of these two tools can affect their effectiveness. Therefore, in this study, the accuracy and efficiency of waterpass and electronic theodolites were measured and analyzed using the cross-section method to gauge the effectiveness of the ABC road construction project in Sumatra. The results show that although the accuracy of the electronic theodolite is lower than that of waterpass, it might be the preferred method because it saves time and reduces the cost of volume measurement, making it both practical and highly efficient.

Keywords: Cut and fill volume; Geodetic method; Road planning; Total station; Waterpass.

ABSTRAK

Pembangunan yang berkelanjutan adalah sebuah konsep popular yang banyak diterapkan saat ini. Salah satu perwujudan dari konsep ini adalah melalui proses perencanaan yang efektif, misalnya dalam perencanaan pembangunan jalan. Pengukuran volume *cut and fill* tanah adalah bagian tak terpisahkan dari proses tersebut, yang menggunakan beberapa metode Geodetik. Metode yang jamak digunakan adalah alat sipat datar *(waterpass)* dan teodolit elektronik *(total station)* dengan perbedaan konsep pengamatan yang signifikan. Perbedaan metode observasi dari kedua alat ini dapat memengaruhi tingkat efektivitas pengamatan. Oleh sebab itu, penelitian ini menggunakan pengukuran dan analisis tingkat akurasi dan efisiensi dari alat sipat datar dan teodolit elektronik menggunakan metode *cross-section* sebagai parameter efektivitas, pada sebuah proyek pembangunan jalan ABC di pulau Sumatra. Hasil penelitian ini menunjukkan bahwa walaupun tingkat akurasi dari teodolit elektronik lebih rendah daripada alat sipat datar, metode tersebut dapat digunakan sebagai metode yang lebih disarankan karena dapat menghemat waktu dan biaya pengukuran volume, sehingga penggunaannya bersifat efektif dan efisien.

Kata Kunci: Metode geodetik; Perencanaan jalan; Sipat datar; Teodolit elektronik; Volume *cut and fill*.

ARTICLE HISTORY

Received: June 3, 2024
Revised: September 11, 2024
Published: November 20, 2024

CITATION (APA 7TH)

Nadzir, Z. A., & Irfansyah, M. (2024). Using geodetic methods in road construction planning: To what extent will it be effective? *Journal of Infrastructure Policy and Management, 7*(2), 167–180. https://doi.org/10.35166/jipm.v7i2.58

INTRODUCTION

Among other principal aspects of managing a country is ensuring infrastructure progress and development. Development is a multidimensional process encompassing various areas, including but not limited to economic, educational, and infrastructural aspects (O'Sullivan & Sheffrin, 2004). Moreover, infrastructure, in particular, plays a foundational role in physical aspects that precede economic growth. Infrastructure also highlights its use in fulfilling almost all human economic needs (Grigg, 1988).

Aligned with the Indonesian government spirit of *'Nawacita'*, which has been promoted over the past decade, the current government of Indonesia has gradually increased the development of infrastructure by 40% compared to the previous period, as reported by the Ministry of Public Works and Housing (KemenPUPR) in 2019 (Hill & Negara, 2019; Singh & Cook, 2016). This surge in infrastructure development projects requires regular and systematic monitoring to support sustainable development. However, this holistic approach has not yet become widely practiced, partly due to the insufficient dissemination of integrated development concepts such as Building Information Management (BIM), WebGIS, remote sensing, and 3D modeling (Beshr, 2015; Gura et al., 2020; Lanari et al., 2020; Nadzir et al., 2021; Scaioni et al., 2018).

Monitoring the development process includes several stages, such as planning and mapping. The concept of mapping cannot be separated from Geodesy or Geomatics. Surveying, or mapping, is the technology, science, and art of determining the relative position of a point (Ghilani & Wolf, 2008). Fundamentally, mapping involves measuring angles and distances. In addition to determining position, the measurement of angles and distances is used to calculate area and volume, commonly known as the cut-and-fill method (Nurjati, 2004).

Currently, volume measurement can be conducted using leveling instruments and electronic theodolites (total stations). The basic principle of both instruments is similar: to collect angle and distance data as calculations for land position and elevation aimed at estimating land volume. However, the difference between these instruments lies in the underlying technology: optical methods in leveling instruments and optical methods assisted by electronic sensors in total stations. This difference affects the accuracy and efficiency of the measurement results (Da Silva et al., 2018). Effectiveness and efficiency are two crucial aspects of maximizing resources in the process of sustainable development, as different methods result in varying levels of effectiveness (Kuzina & Rimshin, 2018; Sestras et al., 2021; Uradziński & Bakuła, 2020).

Understandably, all parties expect efficient and effective construction of highways. The society that will use construction products wishes to undergo pleasant experiences. As for constructors, they aim to effectively and efficiently use the budget. Both parties view that financial budgets can be used optimally to complete the maximum amount of work and that project timelines can be met with the highest level of accuracy (Lamich et al., 2016). Therefore, highway construction should be improved in every aspect, particularly in the measurement and planning stages that rely on geodetic data.

The application of geodetic methods in highway and toll road construction has been widely practiced, yielding varied results and methods, particularly in Europe and the Middle East (Ghorbani et al., 2012; Gikas & Stratakos, 2012; Šafář & Šmejkal, 2015; Sorin Herban et al., 2017). The use of optical methods (theodolites) shows deviations of 2.3 to 3.8 cm in road width measurements (Kriauciunaite-Neklejonoviene et al., 2018), while satellite methods (GPS) demonstrate an accuracy of 3 to 6 cm (Labant et al., 2017). These studies share the focus on measuring the efficacy of such a method, but they fail to incorporate efficiency parameters in their analyses. Additionally, previous research has not explicitly demonstrated the relationship between accuracy and effectiveness with efficiency, nor has it been shown to be significant in highway construction planning processes.

Given the focus of similar studies in Eastern Europe and the Persian and Arabian peninsulas, it is crucial to assess the efficiency and accuracy of volume measurements using two tools—leveling instruments and electronic theodolites. This effort aims to provide recommendations to practitioners for implementing sustainable road construction planning. Furthermore, an analysis of the effectiveness and significance of these two geodetic methods in choosing one over the other during the mapping and planning stages of highway construction is also necessary. In other words, it is essential to understand the degree of effectiveness of these geodetic methods and their significance. These fundamental issues and problems will be addressed in this study, using the ABC location in Sumatra as a case study.

The geodetic method involving leveling instruments (waterpass) has been used since the early 20th century. In contrast, technological advancements in the late 20th century led to the development of the electronic theodolite, commonly known as the total station. Measurements using a waterpass are generally more accurate than the electronic theodolite because optical methods can view farther distances than electronic approaches. However, this advantage comes at the expense of time, as measurements with a waterpass typically take twice as long as other methods (Chekole, 2014; Mukupa et al., 2016). Both methods are used for direct measurement of distances, angles and volume calculations; each is based on the specific principles of the respective tools. Rahayu's (2015) study indicates that both observation methods have nearly identical accuracy in calculating elevation differences and volume estimations based on angle and distance measurements, with discrepancies only in the sub-millimeter range.

Additionally, a comparison between electronic theodolite methods and Unmanned Aerial Vehicle (UAV) methods reveals that although UAV measurements require significantly less time, electronic theodolite provides superior accuracy (Ginting et al., 2024). Other scholars have also used waterpasses as a method in their research.

For example, Wibowo (1987) and Parseno and Yulaikhah (2010) suggest that the underlying conditions of the measurement site do not influence the performance of these tools. Hence, the hypothesis formulated for this study is that while the waterpass method is more accurate than the electronic theodolite, it requires more observation time. In other words, the electronic theodolite demonstrates higher efficiency than the waterpass (Priyadinata & Siregar, 2022), suggesting that the underlying conditions of the measurement site do not influence the performance of these tools.

The commonality among the previous studies mentioned is that none have included parameters of time efficiency and precision for both waterpass and electronic theodolite methods in the context of calculating cut and fill volumes, as performed in as-built surveys of buildings in Bandar Lampung (Nadzir, 2024). Therefore, research focusing on determining accuracy and precision, combined with time efficiency, in the process of volume estimation is essential, and this forms the primary objective of this study. The anticipated outcome of this research is to contribute to the selection of geodetic observation methods in highway planning, aiming for more effective and efficient practices with demonstrable accuracy and quantitative time savings.

THEORETICAL FRAMEWORK

Waterpass and the Electronic Theodolite

Elevation, or height, is a parameter determined by measuring the vertical distance from a reference point (zero point) to another point. In leveling instruments (waterpass), the elevation is calculated as the difference in height between two locations using a leveling staff. This height difference is determined by observing the middle line on the staff at Point 1 and Point 2 and then noting the corresponding values on the staff (Safrel et al., 2018). The output from waterpass measurements includes the vertical height difference and the horizontal distance, which are empirically calculated using the principles of triangles and the Pythagorean theorem.

A theodolite, in principle, measures angles and distances as its two main parameters using optical methods. The instrument is called an electronic theodolite or a total station when electronic systems assist this process. This tool's results include horizontal and vertical angles and distances (Hofmann-Wellenhof et al., 2008). Contextually, the electronic theodolite has advantages in terms of measurement efficiency and time compared to conventional theodolites, although it offers lower levels of accuracy and precision.

An illustration of the theodolite is shown in Figure 1 below.

Figure 1. Electronic theodolite

Efficiency, Effectiveness, Precision, and Accuracy

Efficiency is a measure used to demonstrate how few resources are utilized to complete a task and is typically divided into cost efficiency and time efficiency (Penkov et al., 2019). The distinction between effectiveness and efficiency lies in the perspective used for evaluation. Effectiveness assesses the degree to which a goal is achieved with specific resources, focusing on the outcome or the extent to which the objective is met (Kowacka et al., 2021). In contrast, efficiency focuses on the process, evaluating the activities involved in reaching the goal (Moser et al., 2016). Both parameters are necessary to determine the superiority of one method over another, especially in sustainable planning processes.

Accuracy refers to how close a result or measurement is when compared to an assumed true or reference value. Precision, on the other hand, describes how closely grouped a set of measurements is when repeatedly observing a single parameter. Accuracy is commonly calculated using Root Mean Square Error (RMSE), while precision is determined by analyzing the dataset’s standard deviation. The critical difference between these two formulas lies in the reference value used: RMSE uses an estimated true value, whereas standard deviation relies on the average value. The combination of accuracy and precision defines the overall level of reliability. A dataset is considered to have good reliability when it exhibits both high accuracy and high precision. Conversely, poor reliability is represented by either a high error in accuracy or low precision.

Efficiency and effectiveness metrics, which are combinations of several initial parameters, can be classified into three categories, as illustrated in Table 1. The authors used this table to classify the two observational methods being compared, aiming to present a conclusive analysis of the results and findings.

Table 1. Classification of efficiency and effectiveness

Class	Class	Class	Class	Class
Highly efficient/ effective	< 10 mm	< 10 mm	Faster than the work plan (KAK)	Cheaper than the work plan (KAK)
Efficient/ effective	10-100 mm	10-100 mm	Matches the work plan (KAK)	Matches the work plan (KAK)
Less efficient/ effective	> 100 mm	> 100 mm	Slower than the work plan (KAK)	More expensive than the work plan (KAK)

Volume Estimation Using Cut and Fill Method

The volume of an area in a construction project is a crucial parameter, particularly when building highways, as it involves excavation (cut) and embankment (fill) work on the project site. It is essential because the construction of highways requires a flat surface with minimal elevation differences to adhere to the concept of minimizing energy use in transportation (Macchiarulo et al., 2022; Soilán et al., 2019). Geodetically, the volume of an area can be calculated using the cut-and-fill method based on the topographic map (existing conditions) and the cross-sectional view of the work site. This cross-sectional information is used to determine the planned elevation and the true elevation (existing conditions), which are then divided into areas where excess material must be excavated (cut) and areas that require adding material. The volume of excavation and embankment can be calculated by applying simple geometric concepts, such as the combination of triangular, pyramidal, and trapezoidal shapes. The areas of cut and fill are measured, and their volumes are determined using these geometric approximations. Subsequently, the costs associated with these operations can be estimated in monetary terms (e.g., rupiah per cubic meter), considering the expenses for personnel and other necessary resources.

METHODOLOGY

Research Design

Building upon the state-of-the-art knowledge in applying geodetic methods, particularly in the context of instruments commonly used in Indonesia, this research methodology was carefully selected and designed to be fit for purpose. At the same time, it considers the effectiveness and efficiency outlined in the research hypothesis. The study was conducted on a road construction and planning project spanning 200 meters on the island of Sumatra, which was divided into several observation stations. The measurements were carried out over seven days between February and March, from 08:00 to 15:00 Western Indonesian Time (WIB), under clear weather conditions. Three instruments—GNSS receiver, electronic theodolite, and leveling instrument (waterpass)—were used throughout the seven-day measurement period, with specifications provided in Table 2.

The process began with the horizontal and vertical framework measurements to determine the coordinates of reference points using the GNSS receiver and total station. Subsequently, longitudinal profile measurements were conducted using the leveling instrument and electronic theodolite to generate a longitudinal profile plan. A pre-analysis was then performed to assess the methods' limitations based on the concepts in use. Following this, cross-sectional measurements were carried out using the same two methods, concluding with volume calculations. Finally, the accuracy and efficiency of both methods were calculated, marking the final step of this research. A flow diagram of the research process is illustrated in Figure 2 below, with a particular focus on volume measurements.

Table 2. Instruments used in the research

No	Instrument	Type	Specification
1	Receiver GPS Geodetic	Tpocon Hiper II	Accuracy of the static method = H: 3mm + 0.55ppm, V: 5mm + 0.5ppm Operational time = 14+hour (10 hous TX) Raw data recording = 1 Hz (up to 20 times per second (20 Hz) Operational temperature = -30^{o}C up to 60^{o}C / -22^{o}F up to 140^{o}F
2	Total Station	Topcon GTS 235 N	Diameter of the telescope = 214 mm View area (100 m) = 1^{o}25’ (2.5m/8.2 feet) Zoom in = 24 x Accuracy without micrometer = 2.0 mm (0.08 inch) Accuracy with micrometer = n/a
3	Waterpass	Topcon AT-B4	Diameter of the telescope = 214 mm View area (100 m) = 1^{o}25’ (2.5m/8.2 feet) Zoom in = 24 x Accuracy without micrometer = 2.0 mm (0.08 inch) Accuracy with micrometer = n/a

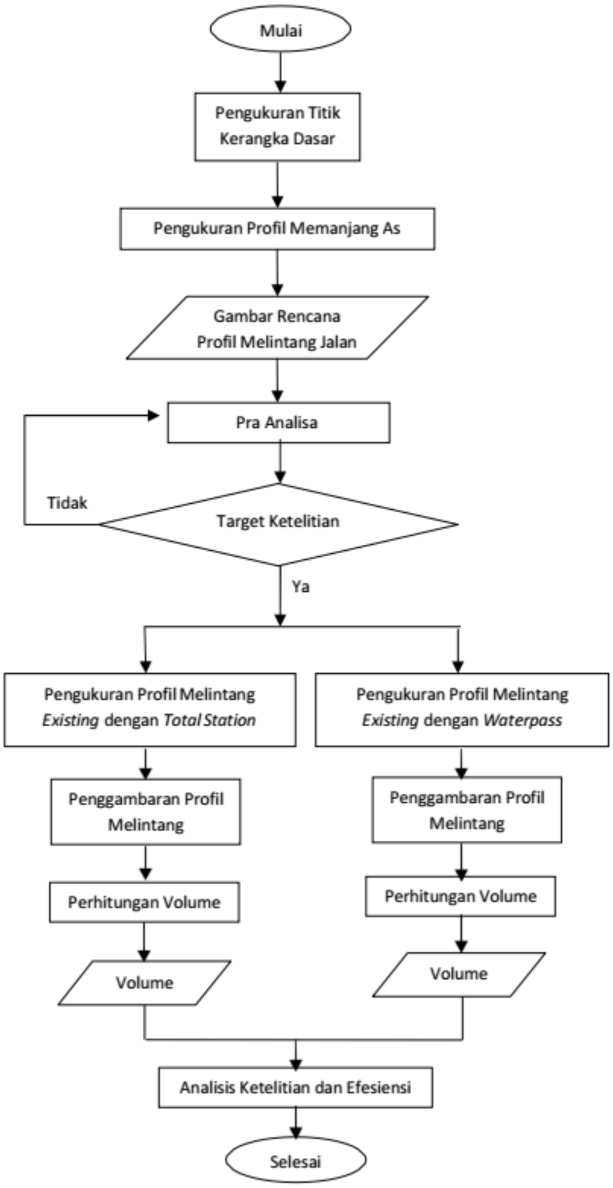

Figure 2. Diagram of the research flow

Data

The reference points used for the horizontal and vertical frameworks consisted of two pillars, named BM01 and BM02, both of which are tied to a global reference system. These pillars were connected to two higher-order reference points: IIT0 for the horizontal axis and IIT5 for the vertical axis. The total number of stations (STA) used in this study was 9, and measurements were taken in two instrument setups. The distance between each STA was 25 meters.

RESULTS AND DISCUSSION

The pre-analysis results for the electronic theodolite, as shown in Table 3, indicate a theoretical accuracy of 25.66 mm. Meanwhile, the pre-analysis for the leveling instrument (waterpass) showed an accuracy of 0.52 mm, demonstrating that the waterpass is 50 times more accurate than the electronic theodolite. This discrepancy can be attributed to how the electronic theodolite measures height, using angles and distances, increasing the margin of error.

Table 3. Pre-analysis result

Parameter	Accuracy (mm)
Z for electronic theodolite	25,657
Elevation difference accuracy	0,520

Table 4. Vertical framework accuracy

Parameter	Value
Average distance calculation (D)	374,9 meter
Precision threshold value	11 mm
Height difference discrepancy	6 mm

The vertical framework measurements in Table 4 show that the forward and backward measurements meet the specifications outlined in the Indonesian National Standard (SNI) number 19-6988-2004, with an LD class for order 4. In other words, the vertical framework measurements are accurate enough to be used in planning a Class 1 highway, as per the applicable regulations. The horizontal framework measurements yielded an accuracy of 1 cm, meeting the accuracy requirements for order 2. Both pre-analysis results suggest that, although the vertical (height) measurements exhibit 2 to 3 times better accuracy, they are more challenging to execute than horizontal (distance) measurements. This is because errors in the z-axis (vertical) increase proportionally with the distance from the observation point, causing error propagation as the distance grows.

Table 5. Data of the elevation profile

STA	Existing elevation (m)	Planned elevation (m)
1	101,598	94,96
2	101,041	94,37
3	100,225	93,62
4	98,669	93,62
5	98,027	94,37
6	96,895	94,96
7	97,441	95,09
8	96,067	95,22
9	97,013	95,09

Table 5 lists the elevations from STA 1 to STA 9 for the longitudinal profile. These values were calculated at the centerline of each station and then used to determine the planned elevation, which was set to a flat gradient of 2%. On average, the difference between the existing and planned elevations was 7.02 meters.

The elevation differences were calculated and plotted in Figure 3 using both measurement methods to observe the trends. It was noted that the elevation difference at STA 4, with a value of 3.5 cm, was the highest, followed by STA 6, with a difference of 2.8 cm. These significant discrepancies at STA 4 and STA 6 can be attributed to the distance between the electronic theodolite's setup position and the stations, resulting in more significant errors.

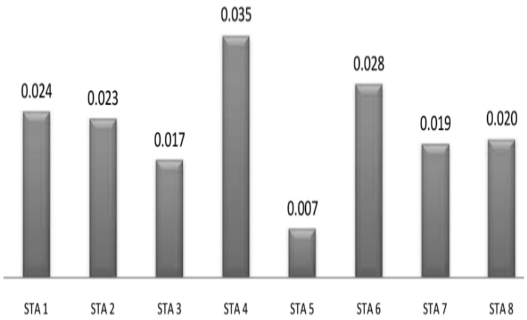

Figure 3. Diagram of the average elevation difference

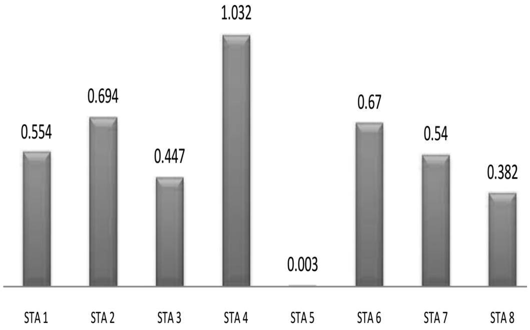

Figure 4. Diagram of the average cross-sectional area difference

Table 6. Cut-and-Fill Volume Calculation

No	STA	jarak	*Waterpass*			*Total Station*			Selisih Volume (m3)
			Luas (m2)	Luas Rerata(m2)	Volume (m3)	Luas (m2)	Luas Rerata(m2)	Volume (m3)	
1	1		91.241			90.687			
		25		81.941	2048.525		81.317	2032.925	15.6
2	2		72.641			71.947			
		25		62.993	1574.825		62.4225	1560.563	14.2625
3	3		53.345			52.898			
		50		30.8175	770.4375		30.078	751.95	18.4875
4	4		8.29			7.258			
		25		17.411	435.275		16.8935	422.3375	12.9375
5	5		26.532			26.529			
		25		35.6025	890.0625		35.266	881.65	8.4125
6	6		44.673			44.003			
		25		51.324	1283.1		50.719	1267.975	15.125
7	7		57.975			57.435			
		25		66.59	1664.75		66.129	1653.225	11.525
8	8		75.205			74.823			
Rata -rata Selisih Volume									13.76

Before estimating the volume, the cross-sectional area difference for each station is illustrated in Figure 4. It can be observed that the same trend occurs, where STA 4 shows the most significant difference, at 1.03 m², followed by STA 2 and STA 6, with a difference of approximately 0.68 m². The cut and fill volume calculation is carried out between two stations; for instance, the volume between STA 1 and STA 2 is referred to as volume 1-2. The results of the estimation are displayed in Table 6. Similar to the previous findings, the most significant volume discrepancy is around STA 4, specifically between STA 3 and STA 4.

Conversely, the most minor volume difference between STA 4 and STA 5 is found. The average cross-sectional area difference can serve as an initial indicator of volume difference. Additionally, the average total volume difference between the waterpass and electronic theodolite methods was 13.76 m³. This difference aligns with the previous subsection's hypothesis and pre-analysis results. However, determining which method is "correct" or "incorrect" falls outside this research scope, as no single value is considered the true reference.

As described in Table 7, the time spent to measure all stations with both methods indicated that the electronic theodolite measurement was 33% faster than the time required to use the waterpass. Regarding efficiency, each point measured with the waterpass took 60% longer than the electronic theodolite, 1.60 minutes compared to 1 minute. This result is related to the measurement procedure of the waterpass, which requires two measurements for correction, and it aligns with the hypothesis presented in the previous chapter.

A comparison of the time efficiency between the two methods, assuming that the measurement of all nine stations does not exceed one day, revealed that with the same amount of time required for waterpass measurements, the electronic theodolite could measure 14 stations, an increase of 5 stations (~50%). Using a simulated distance of 1 km (41 stations), the waterpass method would require 5 days, whereas the electronic theodolite would need 3 days to complete the measurement (40% less time). Furthermore, using an estimate based on the unit prices listed in the Ministry of Public Works Regulation No. 11/PRT/M/2013, the electronic theodolite method could save 31%

in costs (~1 million rupiahs per kilometer) compared to the waterpass method. The time simulation results are presented in Table 8, while the simulation results based on distance and cost are shown in Table 9. These simulations assume equal error levels without error propagation, ensuring proportional and linear values about the time and distance of the measurements.

Table 7. Difference in measurement duration

Types of measurement	Duration
Waterpass	6 hours 42 minutes
Electronic Theodolite	4 hours 1 minute
Difference	2 hours 41 minutes

Table 8. Time-based simulation

Types of measurement	1 day	1 week	1 month
Waterpass	9 STA	45 STA	225 STA
Theodolite	14 STA	70 STA	350 STA

Table 9. Distance-based simulation

Types of measurement	1 km	10 km	100 km
Waterpass	5 days (3 million)	50 days (30 million)	500 days (300 million)
Electronic Theodolite	3 days (2 million)	30 days (20 million)	300 days (200 million)

As seen in Tables 7 through 9, the electronic theodolite demonstrates a clear advantage over the waterpass from the perspective of effectiveness and efficiency based on various simulations. However, it is essential to note that these results must account for all aspects, particularly accuracy and precision.

In addressing the research question regarding selecting the more effective and efficient geodetic method for highway planning, it is evident from Table 1 that the waterpass method falls into the category of effective but less efficient. In contrast, the electronic theodolite method is classified as both practical and highly efficient. Further consideration when selecting the measurement method should ideally begin with a pre-analysis that includes information about accuracy requirements by the Indonesian National Standard (SNI) as an additional consideration. This approach balances the project's needs and the method's capabilities without sacrificing one component to achieve another.

Additionally, attention must be given to the regional applicability of this study's findings to the specific location of the construction project—taking regionality as a critical principle into account. It is one of the main limitations of this research, alongside the absence of a true reference value.

CONCLUSION

Measurements using the waterpass and electronic theodolite methods for estimating cut and fill volumes demonstrated different performances. Regarding theoretical accuracy and precision, the waterpass method performed better than the electronic theodolite. However, this superior accuracy does not necessarily mean that the first method meets the requirements for high-order measurements (order 4 for the waterpass and order 2 for the electronic theodolite).

Table 10. Round-robin Comparison

Parameter	Waterpass	Theodolite
Accuracy and Precision	+ (0,52 mm)	- (25 mm)
Order	- (order 4)	+ (order 2)
Time	- (5 days)	+ (3 days)
Cost	-	+

The simulation results showed that, for an observation distance of 1 km, the electronic theodolite was 1.5 times faster in measurement time and capable of measuring 1.5 times more stations than the waterpass method within the same timeframe. Regarding time efficiency and effectiveness, the second method (electronic theodolite) was more efficient and effective, with a 40.05% time savings. Additionally, regarding the cost, the second method outperformed the first, offering a 31% cost saving per kilometer compared to the waterpass. Table 10 presents the round-robin comparison results between the two methods.

When these factors are combined, it is evident that electronic theodolite is suitable for highway construction projects that prioritize time and cost efficiency, placing it in the effective and highly efficient category. On the other hand, the waterpass method is more appropriate for critical highway construction projects—those requiring a much higher level of accuracy due to the urgency or significance of the project. In conclusion, this study indicates that the electronic theodolite method is better suited for the broad planning of highway projects, except in specific cases where millimeter-level accuracy is required.

RECOMMENDATION

Effective and efficient geodetic observation methods can be introduced and popularized through several mediums in planning and constructing roads. The first medium is through the creation of policy recommendation documents (white papers) by relevant professional associations such as the Indonesian Surveyor Association (*Ikatan Surveyor Indonesia*, ISI) and the Indonesian Engineers Association (*Persatuan Insinyur Indonesia*, PII).

Additionally, the second medium that can be utilized is through standard documents published by policymakers. One potential approach is updating the Indonesian National Standard (SNI) documents related to geodetic observation standards and road construction planning.

The third medium to further embed geodetic methods in road planning is through vocational education at vocational high school, D3/D4 programs, and undergraduate education. This effort would be spearheaded by associations responsible for managing secondary, vocational, and higher education in Geodesy, Geomatics, and Construction.

Moreover, incorporating this topic into technical documents such as the Terms of Reference (TOR) for road construction projects, published by the Ministry of Public Works (Kementrian Bina Marga), would also serve as a highly targeted output.

ABOUT THE AUTHORS

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Editorial Note: The original version of this article was written in Indonesian, titled *"Studi Efektivitas dari Pemanfaatan Metode Geodetik dalam Perencanaan Pembangunan Jalan."* After careful consideration—including the balance of Indonesian/English contents in the journal publication and the potential to reach a broader audience—the article was translated into English with the authors' full consent. The authors have reviewed and approved this translated version for publication.