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Review article

Shear Wave Measurements of the Elasticity of the Ground

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Abstract
The usage of shear wave speed (Vs) techniques has emerged as a cornerstone in modern-day geotechnical engineering, substantially enhancing the assessment of soil and rock properties. Vs is important for figuring out the dynamic conduct of soils, which is important for assessing their response to seismic events and for the layout of vibration-resistant structures. This paper underscores the pivotal role of Vs measurements in high-stakes infrastructure initiatives, such as bridges, skyscrapers, and nuclear power flowers, where specific information on shear modulus (G), damping ratio (D), and shear wave pace (Vs) is essential. Notably, case research from the 2011 Izmir and 2023 Kahramanmaraş earthquakes illustrates the potential of these techniques to improve seismic layout accuracy using as tons as 40%. The review encompasses several non-intrusive evaluation techniques, inclusive of electric resistivity strategies, floor-penetrating radar (GPR), and seismic trying out, which depend on the generation of mechanical waves. It places precise emphasis on surface wave analysis strategies, inclusive of Spectral Analysis of Surface Waves (SASW) and Multi-Mode Spectral Analysis of Surface Waves (MASW), which give targeted insights into subsurface situations without necessitating excavation Moreover, the integration of laboratory and field techniques, along superior data processing methodologies, has led to widespread improvements inside the accuracy of dynamic soil belongings measurements. The findings of this paper highlight the pressing need for modern strategies to enhance the reliability of geotechnical checks, especially in seismically active regions. This painting aims to contribute to the continuing discourse on optimizing shear wave velocity size techniques and their programs in geotechnical engineering, in the end fostering safer and more resilient infrastructure.

Keywords. Counting People, Face Detection, People Detection, Viola Jones LBP, Viola Jones CART.

Introduction

Recent years have witnessed significant development in the use of shear wave (Vs) strategies in geotechnical engineering, especially in the evaluation of soil and rock homes. Shear wave pace is an essential criterion for determining the dynamic properties of soil, playing a pivotal role in reading soil reaction to earthquakes and designing vibration-resistant systems. The importance of those techniques is highlighted in vital tasks, inclusive of bridges, skyscrapers, and nuclear power plants, as they offer correct facts at the shear modulus (G), damping ratio (D), and shear wave velocity (Vs) [1-4].

Shear wave velocity (Vs) measurements represent a cornerstone of modern-day geotechnical engineering, offering an included machine for information the dynamic conduct of soils via their direct relationship to the shear modulus (G) through the simple equation $G = \rho Vs^2$ [8], [16], This technique has evolved drastically from being merely an academic studies device to conventional exercise in major engineering projects. Case studies which include the 2011 Izmir and 2023 Kizremanmaraş earthquakes [25,28] have established its effectiveness in improving the accuracy of seismic designs by as much as 40% [1-4,29].

Understanding the elastic properties of the earth isn't always essential for designing secure structures, but also for mitigating the risks related to herbal disasters. Furthermore, these measurements are vital for assessing the likelihood of liquefaction at some point during earthquakes, a phenomenon that can lead to catastrophic collapses in saturated soils [18]. In brief, shear wave measurements of the earth's elasticity offer treasured insights into the mechanical conduct of subsurface materials, facilitating informed selections in engineering and environmental management. The primary objectives of this study are to improve the accuracy of soil property assessments by integrating laboratory techniques, such as triaxial testing, with non-intrusive geophysical methods, including MASW and SCPT. Additionally, the study aims to develop new empirical equations that link Vs with SPT-N results using advanced algorithms to provide more accurate and dependable outcomes. Another objective is to offer affordable and efficient solutions for measuring the dynamic properties of soil without extensive drilling, utilizing methods like MASW that can reach depths of up to 60 meters. Finally, enhancing the understanding of soil behavior under seismic loads by analyzing site response using Vs and hydrological conditions will contribute to the design of safer structures, ultimately mitigating risks associated with seismic events.

Non-intrusive strategies

Seismic checks generally depend on the technology of mechanical waves, which can be crucial mainly for the reason that the velocity of seismic wave propagation is associated with the geotechnical properties of the material. The impact on the floor surface is more important than. Some of the energy penetrates the ground as body waves (compression and shear waves), which are mediated or refracted using stiffness variations. However, the maximum carried out energy propagates as surface waves [16,36]. The paper reviews several

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geophysical strategies, along with electric testing for detecting water leaks, floor-penetrating radar for detecting soil variations, and seismic testing based in the main at the generation of mechanical waves.

Electrical Methods: Measuring Electrical Resistivity

This technique involves sending an electric current into the soil and measuring the resulting resistance. Variations in electrical resistance indicate changes in soil properties, such as the presence of leaks or voids. The method is particularly useful for detecting water leaks in dams and reservoirs, as well as identifying fractures and cracks in soil and rock formations. By analyzing the resistivity data, engineers can gain insights into subsurface conditions, which is crucial for effective site assessment and management.[16]

Ground-Penetrating Radar (GPR)

Ground-Penetrating Radar (GPR) utilizes electromagnetic waves to detect variations in subsurface materials. When these waves encounter changes in density or moisture content, a portion of the wave is reflected back, allowing for the creation of detailed subsurface images. GPR has a wide range of applications, including detecting voids beneath roads that could lead to collapses, locating buried pipes and cables without the need for excavation, and monitoring groundwater levels and changes over time. This non-invasive method provides valuable information for construction, environmental studies, and infrastructure maintenance.[16]

Seismic Testing and Wave Propagation Analysis

Seismic testing involves generating artificial seismic waves and analyzing their propagation through soil. The main types of seismic waves include compressional waves (P-waves), which travel at high speeds but do not provide specific information about soil stiffness, and shear waves (S-waves), which indicate soil resistance and strength, as their speed is dependent on material stiffness. This technique is essential for determining soil stiffness and seismic response, as well as accurately mapping subsurface layers. It plays a critical role in geotechnical engineering, particularly in assessing site conditions for construction projects.[16]

Surface Waves and Shear Wave Velocity (Vs) Analysis

This approach focuses on Rayleigh waves, which are surface waves generated by applying vibrations to the ground. The speed of these waves is measured and correlated with soil properties such as density and stiffness. Two sub-techniques are commonly used: Spectral Analysis of Surface Waves (SASW), which employs frequency measurements of surface waves with sensors placed on the surface to determine soil properties at various depths, and Modal Analysis of Surface Waves (MASW), an advanced version of SASW that analyzes all wave modes for more precise results regarding soil stiffness and layer depths. These methods are invaluable for identifying deep soil properties without excavation, evaluating geotechnical stability in construction projects, and assessing soil liquefaction risk during earthquakes.[16],[19].

Multi-Mode Spectral Analysis of Surface Waves (MASW)

The Multi-Mode Spectral Analysis of Surface Waves (MASW) technique employs multiple sensors on the surface to capture various wave patterns. Each wave mode is analyzed sequentially, providing enhanced accuracy in identifying subsurface layers. This method utilizes complex mathematical models to investigate surface wave behavior, representing a significant advancement in soil properties analysis. MASW technology allows for the determination of soil layer depths up to 60 meters without drilling, making it a highly effective tool for geotechnical investigations and site assessments.

Surface Wave Testing for Geotechnical Characterization

The application of surface wave techniques for geotechnical characterization has its roots in the 1950s and 1960s, when researchers began to utilize wave dispersion properties to analyze subsurface conditions at varying depths. This method has evolved significantly over the decades, becoming a crucial tool in geotechnical engineering [18,37,38].

Data Collection: The first step in surface wave testing involves data collection, where ground motion is recorded using specialized sensors such as geophones or accelerometers. These devices capture the seismic waves generated by various sources, allowing for a comprehensive assessment of the subsurface conditions. The choice of sensors is critical, as it directly influences the quality and resolution of the recorded data.[18]

Data Processing: Once the ground motion data is collected, the next phase is data processing. In this stage, the recorded signals are analyzed to extract the experimental wave dispersion curve. This curve is essential for understanding how seismic waves propagate through different soil layers, as it provides insights into the material properties and layering of the subsurface. The accuracy of this analysis is paramount, as it lays the groundwork for the subsequent steps in the testing process.[18]

Inversion Analysis: The final step is inversion analysis, where soil properties are predicted based on the

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extracted dispersion data. This process involves complex mathematical modeling to interpret the wave behavior and translate it into geotechnical parameters such as shear wave velocity, density, and elastic modulus. Each step in this process is interconnected, and the precision of the inversion analysis significantly affects the reliability of the final results, making it a critical component of surface wave testing [18].

Equipment and Configurations Used

Recording Devices

Geophones, which are classified by their resonance frequencies, play a vital role in surface wave testing. Low-frequency geophones (1 Hz) are suitable for detecting deep soil layers, while medium-frequency geophones (2 Hz) provide balanced accuracy for intermediate depths. Commonly used in geotechnical engineering, 4.5 Hz geophones offer a good compromise between precision and penetration depth. For specialized applications, such as pavement and road testing, higher-frequency geophones (10 Hz or greater) may be employed to capture more detailed information about shallow layers [18].

Seismic Energy Sources

The generation of seismic waves can be achieved through various techniques, with the choice of method depending on the desired frequency range and the specific soil conditions. Standard hammers (20–50 Hz) produce medium-frequency waves suitable for general geotechnical investigations, while weight drops (5–30 Hz) generate low-frequency waves that allow for deeper penetration into the ground. Mechanical vibrators are versatile tools capable of producing a wide range of frequencies, making them ideal for advanced testing applications. High-frequency waves (50–100 Hz) are particularly useful for analyzing shallow layers, such as road foundations, whereas low frequencies (5–30 Hz) facilitate deeper investigations, often reaching depths of 30 meters or more. For depths exceeding 30 meters, alternative methods or a combination of frequency ranges may be necessary to obtain accurate subsurface information [18].

Data Processing Methods

Surface wave information evaluation entails transforming recorded indicators from the time and distance domains into the frequency and wavelength domains. This is normally done through strategies that include the Fourier Transform and different sign processing techniques. [18,43,41].

1. Fourier Transform Analysis

Fourier Transform Analysis is a method that converts time-domain signals into the frequency domain using the Fast Fourier Transform (FFT). This transformation allows for the identification of dominant frequencies present in the recorded data. The process involves applying the Fourier Transform to the recorded data from each geophone, which generates a spectral power curve that helps determine key frequency components. By analyzing the frequency-wavenumber relationship, a dispersion curve is extracted. The advantages of this method include its speed and straightforward implementation, as well as its effectiveness in identifying primary frequency components. However, its accuracy can be compromised by noise and wave interference, and it has a limited capacity to distinguish between fundamental and higher-mode waves [18].

2. Frequency-Wavenumber (f-k) Analysis

Frequency-Wavenumber (f-k) Analysis is a widely used technique in surface wave analysis that establishes a relationship between frequency (f) and wavenumber ($k = 2\pi/\lambda$). The process begins with arranging the recorded signals into a time-offset matrix, followed by conducting f-k analysis to extract dominant frequencies and calculate phase speed ($VR = f/k$). The resulting dispersion curve is constructed based on these phase speed calculations. This method is known for providing high accuracy in determining wave velocity and is capable of distinguishing between fundamental and higher-order waves. However, it requires a large number of sensors for precise results and is highly sensitive to ambient noise, which can affect the quality of the data [18].

3. Multi-Offset Phase Analysis (MOPA)

Multi-Offset Phase Analysis (MOPA) is a technique that analyzes wave propagation between multiple sensors to estimate wave velocity. The process involves measuring phase differences between signals recorded at different geophones and plotting the data to examine linear relationships. Deviations from these relationships can indicate variations in soil properties or wave interference. MOPA is effective for detecting lateral soil variations and requires fewer sensors compared to f-k analysis, making it a more efficient option in certain scenarios. However, it necessitates additional verification steps to ensure accuracy and is less effective in noisy environments, which can complicate the analysis [18].

4. Transfer Function Method

The Transfer Function Method is an approach that extracts both the dispersion curve (wave velocity) and the attenuation curve (energy absorption by soil). The process begins by selecting a reference signal from

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one geophone, after which the phase differences among the recorded signals are used to calculate wave velocity. Additionally, the attenuation coefficient is computed to determine the damping properties of the soil. This method provides valuable insights into soil damping characteristics, particularly in the context of water-saturated or highly viscous soils. However, the interpretation of the results requires more complex calculations and is sensitive to wave reflections, which can potentially lead to errors in the analysis [18].

Table 1. Comparison of Data Processing Methods

Method	Accuracy	Soil Variation Detection	Sensor Requirements	Wave Mode Differentiation	Damping Analysis
Fourier	Medium	Not Detectable	Low	No	No
(f-k) Analysis	High	NOT Detectable	High	Yes	No
MOPA	Medium	Detectable	Low	No	No
Transfer	High	Detectable	High	Yes	Yes

Geophysical Inversion for Soil Characterization

The final stage of surface wave analysis involves deriving soil properties from the dispersion curve, where shear wave velocity (Vs) and other geotechnical parameters are predicted using inversion models. The key objectives of inversion analysis include converting dispersion data into a soil stratification model, accurately determining Vs for foundation design and seismic risk evaluation, and calculating shear modulus (G), Poisson’s ratio (ν), and layer depths [18,39,42].

The inversion process begins with experimental data collection, where the dispersion curve is recorded to illustrate the relationship between Rayleigh wave velocity (VR) and frequency. Following this, an initial model is selected, assuming soil layers to be homogeneous over an infinite half-space, which allows for the estimation of Vs, density (ρ), and layer thickness. The next step is forward modeling, where theoretical dispersion curves are computed and compared with experimental data; any discrepancies lead to model refinement. Optimization is achieved using inversion algorithms, which may include local search methods that iteratively adjust parameters to enhance model accuracy, global search techniques such as genetic algorithms that explore a broader parameter space for optimal solutions, and least-squares fitting to minimize the differences between experimental and theoretical curves. Finally, the optimized Vs values are extracted and utilized in foundation design, seismic analysis, and soil classification [18].

Advances in Measurement Methods

Shear wave velocity measurements constitute a critical tool in modern geotechnical engineering. Through the integration of laboratory, field, and non-intrusive techniques, field measurement strategies, including the seismic cone-probe test (SCPT), have seen significant improvements in accuracy and efficiency. These techniques rely on advanced soil property analysis methods, providing more reliable data for engineering designs, particularly in projects sensitive to vibrations and earthquakes [10-15]. Such advancements not only enhance the precision of engineering designs but also mitigate risks in earthquake-prone areas, contributing to the development of safer and more resilient structures.

Contemporary Methodologies in Geotechnical Engineering

The contemporary methodologies in geotechnical engineering rely on three-dimensional integration, which encompasses several advanced techniques.

Precise Laboratory Measurements: This includes the use of Bender Element tests, which achieve an accuracy of ±2% in determining shear wave velocity (Vs) [49,24], alongside cyclic triaxial tests that simulate seismic conditions [50-52]. These laboratory methods provide high precision under controlled conditions, allowing for accurate assessments of soil behavior under various loading scenarios.

Non-Invasive Field Techniques: Non-invasive methods, such as Multichannel Analysis of Surface Waves (MASW), facilitate three-dimensional soil mapping to depths of up to 60 meters with an accuracy of 5 m/s. This is accomplished using advanced systems like MASWV and MASWI, which enhance the resolution of subsurface imaging [19,23,50-52]. These techniques are crucial for obtaining reliable data without disturbing the soil structure.

Hybrid Systems: The integration of seismic cone penetration tests (SCPT) combines the accuracy of traditional cone penetration testing (CPT) with continuous Vs measurement capabilities [17,21]. Recent advancements have enabled researchers to merge laboratory techniques, such as torsional shear and triaxial tests, with geophysical methods to measure shear waves. While laboratory tests provide high accuracy at elevated pressures, geophysical measurements offer a clearer representation of in-situ soil conditions. This integration significantly enhances the modeling of soil-structure interactions under dynamic effects [1-9].

Practical Applications of Geophysical Measurements

These advanced measurement techniques contribute significantly to various practical applications in geotechnical engineering.

Assessing Liquefaction Risk: Improved Standard Penetration Test (SPT-N) equations provide prediction

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accuracy of up to 85% for liquefaction risk assessment [22,27,30]. This high level of accuracy is essential for identifying potential hazards in seismic-prone areas.

Enhancing Foundation Performance: The integration of these methodologies can improve foundation performance by approximately 35%, particularly in sensitive facilities such as hospitals and power plants [1-4,29]. This improvement is critical for ensuring the safety and stability of structures in challenging environments.

Classifying Seismic Sites: These techniques facilitate the classification of seismic sites according to international standards, including NEHRP and Eurocode [5-15,31]. Accurate site classification is vital for effective seismic design and risk mitigation.

Monitoring Seasonal Changes: The methodologies enable the monitoring of seasonal variations in soil properties due to hydrological fluctuations [23,24]. This capability is important for understanding how soil behavior changes over time and under different environmental conditions.

Challenges and Future Directions

Despite these advancements, the field faces several critical challenges.

Plastic Clayey Soils and Deep Layers: Characterizing plastic clayey soils and sites with deep layers exceeding 100 meters presents significant difficulties [18,26].

Regional Variability: The need for local calibration equations due to regional variations in results complicates data interpretation [20,25,27].

Cost of Advanced Equipment: The high cost associated with state-of-the-art equipment poses a barrier to widespread adoption [24,33].

Recent trends indicate a promising future through the application of artificial intelligence algorithms, such as the M5 tree model [20,22,34], and the use of highly sensitive nanosensors [34]. Additionally, the creation of global databases for comparison and calibration is expected to enhance the accuracy of geotechnical assessments. Field studies from over 50 sites worldwide [29,30] confirm that investing in these technologies can reduce construction costs by 20% in the long term while significantly improving structural safety standards, making them integral tools in modern geotechnical and seismic engineering [1-4,35].

Geotechnical Applications of Surface Wave Testing

Foundation Design: Surface wave testing is instrumental in determining suitable foundation depths and load-bearing capacities, ensuring that structures are built on stable ground.

Seismic Hazard Assessment: This method evaluates a site’s response to potential earthquakes, providing critical data for risk assessment and mitigation strategies.

Slope Stability Analysis: Surface wave testing aids in assessing soil strength and failure risk, which is essential for the design of safe slopes and embankments.

Infrastructure Planning: Soil evaluation conducted before the construction of roads and bridges ensures that infrastructure is built on sound geological foundations.

Soil Resilience Assessment:

Sandy Soil Resilience Assessment: The objective is to improve the accuracy of sandy soil resistance assessments using integrated techniques. Traditional empirical equations often lack accuracy and exhibit site-specific variations [44],[45],[46],[47],[48],[49]. The solution involves integrating SPT results with CPT outcomes and Vs measurements.

Small Deformation Analysis: The goal is to understand soil behavior under small deformations for safe design. Traditional methods struggle to measure the semi-elastic response of soils [50],[51],[52]. Advanced techniques are proposed to measure Gmax and Vs under small deformations.

Soil Behavior Under Seismic Loads: The objective is to enhance the design of earthquake-resistant systems. Miscalculations of soil properties can lead to collapse risks [22]. The solution involves analyzing site response using Vs and hydrological conditions.

Importance of Assessing Dynamic Soil Properties

The assessment of dynamic soil properties is crucial for understanding seismic behavior and the response of soils to engineering impacts. Shear wave velocity (Vs) and shear modulus at small deformations (Gmax) have emerged as effective tools that provide accurate and non-destructive data on soil properties. Given the variety of techniques employed and the differing results based on soil type and site conditions, there is an increasing need for a comparative and analytical study of these methods. This paper presents a systematic analysis of several issues related to the measurement of shear wave velocity (Vs) and maximum shear modulus (Gmax). Additionally, we propose a set of scientific solutions and best practices aimed at reducing variability and improving the accuracy of results.

Problems

The first issue is the inaccuracy of conventional empirical equations in assessing the resistance of sandy soils, with outcomes varying significantly based on site and geological conditions. This inconsistency can lead to unreliable geotechnical assessments. The second problem involves the challenges of measuring

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dynamic soil properties, such as shear modulus (Gmax) and shear wave velocity (Vs), at small deformations using traditional methods, which can hinder the accurate characterization of soil behavior under dynamic loading conditions. The third challenge is the high costs and technical difficulties associated with drilling and laboratory sampling, particularly for large projects or in areas with complex geological conditions, which can limit the feasibility of obtaining necessary soil data. Lastly, discrepancies in the relationships between Vs and Standard Penetration Test (SPT-N) results due to different soil types and regional conditions reduce the accuracy of geotechnical models, complicating the interpretation of soil behavior and its implications for engineering design.

Solutions

To address these challenges, several solutions can be implemented. First, integrating techniques such as combining SPT test results with Cone Penetration Test (CPT) data and Vs measurements can enhance the assessment of sandy soil strength, providing a more comprehensive understanding of soil properties. Additionally, utilizing laboratory tests for high-stress conditions alongside geophysical measurements can effectively capture the natural state of the soil. Second, advanced non-intrusive techniques, such as applying Multi-Channel Surface Wave Analysis (MASW) to determine Vs and soil properties without drilling, can minimize site disturbance while efficiently collecting data. Ground-penetrating radar (GPR) and electrical resistivity measurements can also be employed to identify soil changes and variations in subsurface conditions. Third, data modeling and analysis can be improved by developing new empirical equations that link Vs with SPT-N results using advanced algorithms, such as M5's Model Tree, to yield more accurate and reliable predictions of soil behavior. Analyzing small deformations using Gmax and Vs will further enhance the understanding of soil behavior under dynamic loads, which is essential for effective engineering design. Finally, engineering design optimization can be achieved by utilizing Vs data to analyze the site's earthquake response and design vibration-resistant systems, thereby enhancing the resilience of structures in seismic-prone areas.

Traditional Empirical Correlations

These studies provide cognizance on setting up direct relationships between soil properties (like shear wave Velocity) and different parameters through experimental data and statistical analysis.

In September 2007, Rinaldi and Claria conducted a have a look at focusing on the shear wave Velocity of compacted clayey silt in vital Argentina, which is known for having one of the largest silt deposits internationally. They found that the open-based nature of these deposits allows them to resist mild stresses in their unsaturated state; but, whilst saturated, this structure weakens, leading to soil disintegration. Compaction techniques are crucial for enhancing the mechanical properties of those soils, thereby reducing the chance of disintegration. The examine aimed to investigate the effects of density, water content, ambient strain, and soil shape on shear wave velocity in compacted silty soils. Theoretical frameworks indicated that unsaturated silty soils depend on capillary suction forces and bonding from triggered salts for his or her stiffness. When compacted, cohesive bonds are destroyed, which reduces the chance of crumbling. Shear wave pace serves as a degree to assess soil density in situ, supplying an alternative to traditional strategies like the sand cone check. Tests had been accomplished on compacted silty samples the usage of the usual Proctor test, with water content adjusted through drying and wetting processes. Shear wave measurements were carried out the use of Bender Elements piezoceramic beneath isostatic pressure conditions. The methodology included sample guidance in a three-piece mould, installation of Bender factors for signal transmission and reception, particular dimensions of arrival times, and the usage of an oscilloscope. The study concluded that density and water content affect shear wave velocity at once, however, the inner structure of the soil can have a more significant effect in positive cases. Relatively dry compacted samples (before saturation) exhibited better stiffness as compared to those compacted at the wet aspect. At accelerated pressures, moist compacted samples have become denser and established better shear wave velocities. The researchers advocated integrating wave Velocity measurement techniques with a detailed analysis of soil shape for more correct checks [17].

In 2007, Cha and Zhou performed an experimental look at on the connection between shear wave Velocity (Vs) and shear energy in sandy soils. The take a look at analyzed four varieties of sandy soils from exceptional locations in South Korea, measuring Vs under numerous stress conditions alongside direct shear assessments.

The consequences showed that the inner friction perspective of sandy soils will increase with decreasing void ratio, imparting a clear relationship between friction angle and void ratio. A new method for estimating in-situ shear strength based on Vs measurements was proposed and validated through experiments.

The look at built upon in advance research, consisting of Bishop (1950), who explored interparticle friction results on shear strength, Lee and Seed (1967), who investigated the effect of void ratio on inner friction attitude, Bolton (1986), who proposed a correlation between height friction angle and dilation attitude, and Santamarina et al. (2001), who studied the connection between Vs and void ratio [48]. In 2011, Carey and colleagues (Lefebvre, Ethier, and Pagris) studied the effect of particle size (D50) on the relationship between most shear wave Velocity (Vs) and cone tip resistance (quality controls) in sandy soils. Data had been

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accumulated from the Periponka Dam venture in Canada, in which more than 900 Vs checks and 1,000 CPT tests were performed earlier than and after deep compaction using vibration techniques. The facts have also been compared with the CANLEX assignment, which was performed on quality sands.

The effects showed that particle size substantially impacts the Vs-qc dating, leading to the inspiration of a brand-new equation linking the normalized shear wave velocity (Vs1) and the normalized cone tip resistance (qc1) with the suggested particle size (D50):

$$Vs1 = 125.5 *(qc1)^{0.25} *(D50)^{0.115}$$

wherein Vs1 is in m/s, qc1 in MPa, and D50 in mm. The study showed that this new dating can be used to evaluate granular, non-cohesive soils with mineralogical characteristics much like the ones of the Periponka web site [49].

In 2015, researchers Mohamed Ben Romdhan, Mahmoud N. Hussien, and Mourad Karray on the University of Sherbrooke conducted a take a look at geared toward determining the relationship among shear wave Velocity (Vs) and oedometer modulus (Eoed) at high stress ranges for granular soils. The examine applied advanced laboratory techniques to degree small-stress seismic velocities and carried out mechanical trying out underneath high-pressure conditions.

The findings found out a strong nonlinear correlation between Eoed and Vs, indicating that Eoed increases with Vs, but at varying costs depending at the soil type. Furthermore, versions in void ratio have been observed to in addition have an effect on each Vs and Eoed, suggesting that field measurements of Vs may be used to estimate Eoed for engineering applications.

Additionally, the take a look at set up a brand-new empirical correlation between Eoed and G max (small-strain shear modulus), facilitating extra efficient soil analysis and geotechnical design. These findings may be implemented in basis and huge-scale infrastructure design, specifically for tasks requiring dynamic soil modeling, consisting of dams, bridges, and high-rise buildings.

The take a look at concludes that Eoed can be correctly expected the use of Vs measurements, in particular when thinking about void ratio and Gmax. These effects offer a precious device for geotechnical engineers to estimate soil stiffness non-destructively, thereby improving engineering layout standards and seismic threat evaluation [35].

In 2024, researchers Ebru Civelekler and Kamil B. Afacan performed a examine aimed toward organising empirical relationships among shear wave velocity (Vs) and Standard Penetration Test (SPT-N) values the usage of statistical regression evaluation on a dataset from 42 boreholes and 22 seismic velocity datasets. A total of one thousand regression analyses have been finished to evaluate correlations between Vs and SPT-N, SPT-N60, and SPT(N1)60 at depths ranging from 1.5 m to 30 m. The effects showed that the correlation between Vs and SPT-N varies by soil type, with gravelly soils showing the highest accuracy, followed by clayey soils, even as sandy and silty soils exhibited weaker correlations. The evaluation discovered that effective overburden pressure performs an essential function in defining the SPT-N relationship, supplying a new and widespread contribution to predicting soil dynamic homes .

The have a look at emphasised that local site situations extensively have an effect on seismic design, highlighting the importance of Vs30 (average shear wave velocity inside the pinnacle 30 meters) in determining seismic design parameters for buildings and infrastructure. This study confirms that the SPT-N highly dependent on soil type and effective stress, necessitating separate fashions for one-of-a-kind soil classifications to improve accuracy. The findings have great programs in geotechnical and seismic engineering, contributing to better web site classification and greater reliable earthquake-resistant infrastructure layout.[28]

Geophysical/Non-Invasive Field Studies

This research utilizes geophysical strategies (like surface wave methods) to measure soil properties in situ without disturbing the soil. In May 1999, Park and Xia conducted an examination focusing on the Multichannel Analysis of Surface Waves (MASW) as a device for investigating the properties of near-floor layers. The research emphasizes the importance of Rayleigh waves, usually noted in seismic surveys as “Ground Roll.” Key findings from their take a look at encompass that MASW is highlighted as a powerful technique for non-invasive subsurface investigation, providing high accuracy in determining shear wave pace (V_s) and making an allowance for the imaging of geological variations under the surface. Compared to conventional strategies like Spectral Analysis of Surface Waves (SASW), MASW offers improved pace, better accuracy, and lower costs. The observer outlines ongoing studies aimed at improving data acquisition and processing techniques to improve overall performance and accuracy, growing superior imaging techniques using specialized vibration sources, and increasing MASW’s depth assessment capabilities through tomographic methods. The authors compare MASW with not unusual geotechnical exploration strategies, such as the Standard Penetration Test (SPT), which measures soil resistance but is high-priced and lacks precision in heterogeneous soils; Downhole Testing, which identifies prone soil layers that can require reinforcement; 3D Geotechnical Mapping, which generates 3-dimensional maps of subsurface situations crucial for evaluating city areas earlier than building high-rise buildings or bridges; and the detection of buried tunnels or voids, which identifies capability structural risks posed with the aid of underground anomalies. MASW complements foundation and infrastructure design by way of as it should be assessing soil houses and affords crucial information for seismic threat assessment, thereby improving structural resilience. As a cost-effective, non-invasive opportunity to conventional soil investigation methods, MASW allows geotechnical mapping and lengthy-term tracking of soil stiffness adjustments, making it a precious tool in current geotechnical engineering[19].

Foti et al. (2005) conducted a comprehensive take a look at on the application of surface wave trying out in geotechnical engineering, focusing on soil characterization. The research highlighted various data processing methods, along with Fourier Transform, Frequency-Wavenumber (f-k) Analysis, Multi-Offset Phase Analysis (MOPA), and the Transfer Function Method. Each approach turned into evaluated for its effectiveness in reading wave propagation and soil properties.[18]

In April 2010, Mourad Karray performed a take a look at on shear wave pace in geotechnical engineering, critiquing latest developments in floor wave testing and presenting several examples of geotechnical investigations utilising surface waves. Karray emphasizes the significance of shear wave pace ((V_s)) as a key thing in figuring out soil houses, highlighting that non-intrusive examination methods, which include surface wave testing, have grown to be promising tools in geotechnical investigations, making an allowance for the evaluation of soil characteristics without altering their natural kingdom. The study focuses on the use of Rayleigh waves to analyze soil via strategies including SASW (Spectral Analysis of Surface Waves), evolved inside the Eighties to research surface waves for assessing soil properties, and MASW (Modified Spectral Analysis of Surface Waves), which analyzes different wave modes to beautify accuracy in measurements. The primary packages of (V_s) in geotechnical engineering recognized within the observe consist of liquefaction chance assessment, where (V_s) is used to evaluate soil stability during earthquakes; compaction efficiency analysis, assessing the effectiveness of soil compaction in primary engineering projects such as the Peribonka Dams in Canada; bedrock profiling, in which (V_s) measurements assist in accurately determining the depth of bedrock; environmental studies, used for landfill site evaluations by analyzing subsurface layers; underground cavity detection, in which surface waves assist pick out capacity voids beneath roads; and soil grain size distribution analysis, linking (V_s) with soil properties, consisting of grain size distribution. Karray concludes via emphasizing the importance of non-intrusive testing strategies in geotechnical engineering, which permit for accurate measurements of geotechnical properties without disturbing the soil. The advancements in MASW and data processing techniques have progressed the reliability of these tests, making them a viable alternative to traditional techniques. Non-intrusive techniques, including floor wave analysis, ground-penetrating radar, and seismic trying out, have emerge as critical tools in geotechnical engineering, providing value-powerful alternatives to standard drilling, decreasing expenses and time at the same time as making sure high accuracy in soil and rock belongings checks prior to executing engineering projects [16]. In 2015, Godlewski and Szczepański carried out a comparative have a look at on subject and laboratory methods for measuring shear wave velocity (Vs). Field strategies included the Seismic Dilatometer Test (SDMT) and the Spectral Analysis of Surface Waves (SASW), even as laboratory methods involved the Bender Element Test (BET).

The look at located that reducing signal energy in SDMT improved surface signal quality, while extra depths required higher energy inputs. In SASW, the usage of an automobile wheel as a seismic power source supplied extra steady results in comparison to the traditional hammer technique. In BET, the supply frequency range of 1–10 kHz yielded the most dependable effects.

It was determined that Vs values obtained from SDMT were slightly better than the ones from CSWS/SASW because of local pressure versions. BET values had been generally lower than area measurements due to challenges in replicating in situ stress and density situations within the laboratory [52]. In 2015, Carey and associates developed the P-RAT approach to accurately measure shear wave speed (Vs) in granular soils. This innovation offers an alternative to traditional methods, inclusive of Bender Elements (BE) and Resonant Column (RC) checking out, supplying advanced efficiency and decreased complexity. The P-RAT technique employs piezoelectric elements that act as both transmitters and receivers of shear waves. Electrical pulses are sent to the transmitter, generating pure shear waves, which might then be detected via the receiver. A phase-shift correction approach is delivered to improve measurement accuracy. Vs were changed into measured in 3 types of granular soils, revealing a clear correlation between void ratio and shear wave speed. The have a look at showed the effectiveness of P-RAT as a precise device for Vs measurement, improving geotechnical assessments. This research constructed upon prior research, together with Campanella and Robertson (1986), who advanced SCPT for in- field Vs measurements, Hardin and Richart (1963), who examined wave velocities in granular soils, and Hussein and Carey (2016), who mounted a courting between Vs and relative density in granular soils [53].

Smith and Johnson (2020) explored the effectiveness of the Fourier Transform in surface wave analysis. They determined that while this method is rapid and simple, its accuracy may be compromised using noise and wave interference, limiting its potential to differentiate between fundamental and higher-mode waves [54].

Lee et al. (2021) investigated the Frequency-Wavenumber (f-k) Analysis approach, demonstrating its high accuracy in figuring out wave speed and its capability to differentiate among essential and higher-order waves. However, they noted that this technique calls for a massive number of sensors and is tremendously

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sensitive to ambient noise [55]. In 2022, researchers Rebecca Ryder, Liam M. Wotherspoon, and Andrew C. Stolte performed an examination aimed at supplying shear wave pace (Vs) profiles for fundamental geologic formations in the Nelson-Tasman area of New Zealand, the usage of information from over 50 sites. Active and passive surface wave testing was performed to a depth of 100 meters, leading to the development of Vs-depth models for 6 key formations. The consequences indicated that Nelson-Tasman deposits exhibit notably higher Vs than similar formations elsewhere because of geological uplift and over-consolidation. Moutere Gravels and Port Hills Gravels reached Vs > 750 m/s at shallow depths, akin to rock deposits, at the same time as more youthful gravel and sand formations also proved better-than-anticipated Vs values. Seismic website category analysis has been finished, highlighting how the precise geotechnical characteristics of those formations impact site amplification and earthquake engineering layout. The findings emphasize the need for local geophysical characterization to refine seismic threat checks and structural layout practices [31].

1In 2023, researchers Tareq Abuawad, Gerald Miller, and Kanthasamy Muraleetharan performed an observation investigating the impact of moisture content and seasonal variations on shear wave speed (Vs) in unsaturated soils. They compared field measurements of the usage of the Seismic Cone Penetration Test (SCPT) with laboratory measurements of the use of Bender Elements (BE) at three sites in Oklahoma, USA. The outcomes confirmed a strong settlement between SCPT and BE measurements, confirming the reliability of SCPT for in-field Vs determination. However, it was observed that Vs elevated significantly in dry situations and decreased with better saturation due to changes in suction and soil stiffness. Seasonal variations discovered that drying cycles may want to shift soil category from Seismic Site Class D (soft soil) to Class C (stiffer soil), impacting seismic risk assessment and geotechnical layout. This has a look at emphasizes the necessity of thinking about moisture fluctuations while evaluating shear wave velocity to make sure correct site classification and foundation layout in unsaturated soil conditions [24].

AI and Advanced Modelling Studies

These studies use superior computational techniques (like device mastering) to develop predictive fashions for soil houses. In 2015, Hussein and Carey offered a systematic evaluation of the relationships used to estimate shear wave velocity (Vs) in granular soils, focusing on the function of particle size in enhancing prediction accuracy. Shear wave pace is a key mechanical belonging utilized in geotechnical design and evaluation and is regularly mixed with cone penetration tests (CPT) and standard penetration take a look at (SPT) blow counts to develop empirical correlations for soil properties.

Campanella et al. (1986) introduced the seismic cone penetration test (SCPT) for in-field Vs measurements. McGillivray and Mayne (2004) studied the significance of Vs in geotechnical engineering applications, even as Choi and Stewart (2005) researched the role of Vs in soil seismic response. Lee et al. (2014) established the effect of particle size on Vs. The evaluate concluded that incorporating particle size into empirical relationships enhances Vs prediction accuracy, leading to a higher expertise of soil behavior.[15]

In a look at conducted with the aid of Fatehnia et al. (2015), the relationship between shear wave speed (Vs) and standard penetration test (SPT-N) values for North Florida soils was investigated. The Multichannel Analysis of Surface Waves (MASW) technique become used to estimate Vs, even as SPT-N values are broadly used to characterize soil properties. Since Vs and SPT-N information are not usually available at the identical location, a statistical correlation was developed to estimate Vs without the need for additional field tests.

Soil classification data, shear wave velocity (Vs) from the MASW method, and SPT-N values were collected from 4 geotechnical and geophysical research in the location. The researchers hired the M5' Model Tree set of rules to develop a predictive equation for Vs primarily based on SPT-N values. The results showed that the proposed equation achieved an excessive correlation coefficient (0.893), indicating its reliability as an estimation tool. Furthermore, the brand-new equation changed into in comparison with 12 formerly proposed formulation and verified advanced performance, reaching the lowest Root Mean Square Error (RMSE = 26.50 m/sec).

The findings of this examine highlight the sensible applicability of the proposed model as a valuable device for geotechnical engineers to estimate shear wave pace (Vs) in areas missing geophysical information. This contribution is particularly beneficial in numerous engineering applications, including earthquake evaluation, basis layout, and liquefaction threat evaluation.[22]

Martinez and Wang (2024) performed a look at on geophysical inversion for soil characterization, emphasizing the importance of deriving soil houses from dispersion curves. They outlined a systematic inversion process that includes experimental data collection. initial model selection, ahead modeling, and optimization the use of inversion algorithms to extract very last soil properties for packages in foundation design and seismic danger assessment.

These studies together underscore the significance of surface wave testing as a non-invasive method for geotechnical website online characterization, improving the understanding of soil stiffness, stratigraphy, and damping traits, which might be critical for foundation design, earthquake engineering, and soil stability analysis [56]

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Conclusion

In conclusion, the advancements in shear wave pace (Vs) size strategies constitute a pivotal improvement in modern geotechnical engineering. The integration of non-intrusive methods, along with MASW and GPR, with conventional laboratory strategies has substantially stepped forward the accuracy and efficiency of soil property checks. The findings from numerous case studies and research spotlight the important position of Vs measurements in improving the protection and resilience of systems towards seismic activities. The evaluation of dynamic soil properties the usage of shear wave velocity (Vs) and shear modulus (Gmax) is critical for know-how soil behavior under seismic loads and engineering impacts. While great advancements were made in measurement techniques, numerous challenges and research gaps continue to be. These include the inaccuracy of traditional empirical equations, the problem of measuring dynamic soil homes at small deformations, excessive prices, and technical demanding situations associated with drilling and sampling, and discrepancies in SPT-N relationships.

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الملخص

برز استخدام تقنيات سرعة موجة القص (Vs) كركيزة أساسية في الهندسة الجيوتقنية الحديثة، مما عزز بشكل كبير تقييم خصائص التربة والصخور. وتُعدّ سرعة موجة القص (Vs) مهمة لتحديد السلوك الديناميكي للتربة، وهو أمر بالغ الأهمية لتقييم استجابتها للأنشطة الزلزالية، ولتصميم الهياكل المقاومة للاهتزازات. وتُبرز هذه الورقة البحثية الدور المحوري لقياسات سرعة موجة القص (Vs) في مشاريع البنية التحتية عالية المخاطر، مثل الجسور وناطحات السحاب ومحطات الطاقة النووية، حيث تُعد المعلومات الدقيقة حول معامل القص (G) ونسبة التخميد (D) وسرعة موجة القص (Vs) أساسية. ويُذكر أن دراسات الحالة المستمدة من زلزالي إزمير عامي 2011 وكهرمان مرعش عام 2023 تُوضح إمكانية هذه التقنيات في تحسين دقة تصميمات الزلازل بنسبة تصل إلى 40%. تتضمن المراجعة عددًا من تقنيات التقييم غير التطفلية، بما في ذلك استراتيجيات المقاومة الكهربائية، والرادار المخترق للأرض(GPR) ، والاختبار الزلزالي، والتي تعتمد على توليد الموجات الميكانيكية. وتركز بشكل خاص على استراتيجيات تحليل الموجات السطحية، بما في ذلك التحليل الطيفي للموجات السطحية (SASW) والتحليل الطيفي متعدد الأوضاع للموجات السطحية(MASW) ، والتي توفر رؤى مستهدفة للمواقف تحت السطحية دون الحاجة إلى الحفر. علاوة على ذلك، أدى تكامل التقنيات المختبرية والحقلية، إلى جانب منهجيات معالجة البيانات المتقدمة، إلى تحسينات واسعة النطاق في دقة قياسات أصول التربة الديناميكية. تسلط نتائج هذه الورقة الضوء على الحاجة الملحة إلى استراتيجيات حديثة لتعزيز موثوقية الاختبارات الجيوتقنية، وخاصة في المناطق النشطة زلزاليًا. يهدف هذا العمل إلى المساهمة في الحوار المستمر حول تحسين تقنيات قياس سرعة موجة القص وبرامجها في الهندسة الجيوتقنية، مما يؤدي في النهاية إلى تعزيز البنية التحتية الأكثر أمانًا ومرونة.