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Research Article

Development of a Modular Multi-Segment Rock–Soil Sampler for Adaptable Geotechnical Exploration

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Abstract

Subsurface investigation often requires sampling tools that can operate under variable ground conditions and depths. Conventional soil and rock samplers are typically manufactured with fixed dimensions, which may reduce operational flexibility during field exploration. This study presents the development of a modular multi segment rock soil sampler intended to improve adaptability in geotechnical investigations. The proposed system consists of a penetration head, sequential cylindrical sampling segments, an internal sample holding section, and a base connection interface. The multi segment configuration enables the sampler to be assembled in different lengths according to exploration requirements. The penetration head is designed to facilitate entry into compact soil or weathered rock formations while guiding fragmented material into the sampling chamber. The modular architecture allows individual segments to be detached, inspected, or replaced without replacing the entire tool assembly. Conceptual modelling and structural evaluation were carried out to examine the geometry and operational arrangement of the sampler. The developed system demonstrates improved adaptability, easier handling during field deployment, and simplified maintenance. The proposed sampler offers potential benefits for geotechnical exploration where flexible sampling depth and equipment portability are important operational considerations.

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1. INTRODUCTION

Subsurface characterization is a fundamental component of geotechnical engineering, mining exploration, and infrastructure development. Reliable assessment of soil and rock properties requires representative samples collected from the ground through systematic field investigation procedures. The quality of these samples significantly influences the accuracy of laboratory testing results and the reliability of engineering design parameters derived from them [1,2]. Sampling procedures therefore play a critical role in determining the mechanical behavior of subsurface materials used in engineering analysis.

Field sampling methods have been widely developed and standardized for geotechnical investigations. Disturbed soil samples are commonly obtained using split barrel samplers during the standard penetration test procedure, which is widely applied for estimating soil resistance and relative density in subsurface investigations [3]. For relatively undisturbed sampling of cohesive soils, thin-walled tube samplers such as Shelby tubes are often used in accordance with established testing practices [4]. In rock formations, rotary drilling techniques are commonly employed to obtain cylindrical cores that can be examined for structural and mechanical characteristics of the rock mass [5]. These sampling techniques have formed the basis of geotechnical exploration for several decades.

Despite the widespread use of conventional sampling tools, several operational limitations have been reported in the literature. One of the primary challenges is the disturbance introduced during sampling operations, which may alter the natural structure of soils and weak rocks [6]. Disturbance can occur due to excessive penetration resistance, friction along sampler walls, or improper cutting geometry of the penetration head [7]. Such disturbances may significantly affect laboratory measurements of strength, compressibility, and permeability, leading to uncertainty in engineering design parameters [8].

Another limitation associated with conventional sampling tools is their fixed structural configuration. Most commercially available samplers are manufactured with predetermined lengths and diameters, which restricts their adaptability during field exploration [9]. When investigation depths vary across different locations within a project site, multiple sampling tools with different dimensions may be required. This requirement increases logistical complexity and equipment costs during site investigation programs [10]. Additionally, rigid structural designs often complicate maintenance procedures because damage to one component may require replacement of the entire tool assembly rather than a single part [11].

Geotechnical site investigation practices have evolved significantly with advances in drilling technologies and exploration equipment. Modern exploration activities often require flexible and adaptable systems that can operate efficiently under variable field conditions [12]. Modular mechanical systems have gained attention in many engineering applications because they allow components to be assembled or replaced individually without compromising the functionality of the overall structure [13]. Such modular concepts have been successfully applied in drilling equipment, exploration rigs, and other mechanical systems used in subsurface engineering activities [14].

The design of sampling tools also depends heavily on the penetration mechanism used to enter the ground. Efficient penetration requires appropriate cutting geometry capable of fragmenting soil or weathered rock while minimizing disturbance to the surrounding material [15]. The configuration of the penetration head influences both the penetration resistance and the quality of collected samples [16]. Cutting heads with multiple contact edges have been used in drilling and excavation systems to improve penetration efficiency and reduce operational resistance [17]. Incorporating similar design concepts in sampling devices may improve their performance in heterogeneous ground conditions.

The internal structure of the sampler is another important factor affecting sample quality. The design of the sampling chamber must allow efficient entry of soil or rock fragments while preventing excessive disturbance during retrieval of the device from the ground [18]. Proper chamber geometry can help retain collected material and reduce the loss of samples during extraction [19]. Several studies have emphasized the importance of maintaining the natural condition of samples to ensure reliable laboratory testing results [20].

Field operations in remote mining and geotechnical investigation sites also introduce logistical challenges related to transportation and equipment handling. Large rigid sampling tools may be difficult to transport over long distances or through difficult terrain [21]. Equipment that can be disassembled into smaller components can provide advantages in terms of portability and ease of handling during field investigations [22].

Given these challenges, there is increasing interest in developing adaptable sampling systems capable of addressing operational limitations associated with conventional rigid tools. A modular multi segment sampling device represents one possible approach to improving adaptability in subsurface investigations. By allowing the structural length of the sampler to be adjusted through detachable segments, such systems may provide greater flexibility during exploration programs where investigation depths vary across different locations [23].

The concept of modular design has been widely used in engineering systems to improve maintainability and operational efficiency [24]. In the context of subsurface exploration, a modular sampler could simplify equipment maintenance because individual segments could be replaced independently when damaged [25]. This feature may reduce equipment downtime and improve efficiency during extended field investigations.

Furthermore, the use of detachable segments may improve the transport and storage characteristics of sampling equipment. Instead of transporting a single long tool, field operators can transport individual segments and assemble the device at the investigation site according to the required sampling depth [26]. Such adaptability is particularly beneficial for geotechnical investigations conducted in remote locations where transportation of large equipment is difficult.

Based on these considerations, the present study focuses on the development of a modular multi segment rock soil sampler designed to improve adaptability during geotechnical exploration. The proposed device incorporates a penetration head, detachable cylindrical segments, a sampling chamber, and a base connection unit that allows attachment to penetration equipment. The objective of the study is to present the conceptual design and functional configuration of the sampler and to evaluate its potential advantages compared with conventional sampling tools used in subsurface investigations.

2. MATERIALS AND METHODS

The development of the modular multi segment rock soil sampler was carried out through a structured engineering design procedure that included conceptual design, component configuration, geometric modelling, and operational evaluation. The objective was to design a sampling system capable of adapting to different exploration depths while maintaining structural stability during penetration and retrieval operations. The design process began with an evaluation of commonly used soil and rock sampling tools employed in geotechnical exploration. Observations from conventional devices highlighted limitations related to fixed structural length, transportation difficulty, and replacement of damaged components. These observations guided the development of a modular system composed of several detachable segments that could be assembled according to exploration requirements.

The proposed sampler was designed to consist of four primary functional units including a penetration head, sequential cylindrical segments, a sample collection section, and a rear connection unit for attachment to driving equipment. The penetration head was designed to initiate contact with the ground surface and facilitate entry into soil or weathered rock layers. The geometry of the head was configured to concentrate applied force at the contact interface so that material fragmentation could occur during penetration. The fragmented particles were directed toward the internal chamber positioned immediately behind the penetration head. The internal chamber was designed as a cylindrical cavity to temporarily retain collected material until the device was extracted from the ground.

The structural body of the sampler was composed of multiple cylindrical segments connected along the longitudinal axis. Each segment contained a connection interface that allowed secure attachment with adjacent segments. The connection interface was designed to maintain alignment between segments and to ensure that axial forces applied during penetration could be transmitted along the entire length of the sampler. The modular arrangement allowed the number of segments to be varied depending on the depth of investigation. This configuration provided flexibility during exploration because the device could be assembled using only the required number of segments before field deployment.

The rear portion of the sampler included a base connection interface that allowed attachment to manual driving rods or mechanical penetration equipment. This connection ensured that the penetration force could be transferred efficiently from the driving system to the penetration head. During operation the assembled sampler was positioned vertically on the ground surface and axial force was applied through the driving rod. As penetration progressed the cutting geometry at the front of the device facilitated entry into the soil or rock mass while directing fragments into the sampling chamber.

The modular system was also evaluated in terms of operational assembly and handling procedure. The sequential assembly of segments allowed the device to be transported as individual components rather than a single long structure. This arrangement simplified transportation and storage particularly during remote field investigations. After sampling the device could be removed from the ground and the segments separated sequentially in order to retrieve the collected material from the chamber. The primary functional components and their roles within the sampler configuration are summarized in Table 1.

Table 1: The primary functional components and their roles within the sampler configuration

Component	Description	Functional role
Penetration head	Front cutting section of the sampler	Initiates penetration and fragments soil or rock material
Cylindrical segments	Detachable structural sections	Provide adjustable length and maintain axial alignment
Sampling chamber	Internal cavity behind the penetration head	Retains collected soil or rock fragments
Base connection unit	Rear coupling section	Connects the sampler with the driving rod or penetration equipment

The geometric considerations adopted during the development of the sampler focused on maintaining stability and efficient sample collection. Important design parameters included the length of each segment, the external diameter of the cylindrical body, and the internal capacity of the sampling chamber. These parameters influence the penetration behaviour and the volume of collected material. The conceptual geometric parameters used in the design stage are presented in Table 2.

Table 2: The conceptual geometric parameters used in the design stage

Parameter	Description	Design purpose
Segment length	Length of individual modular section	Determines achievable sampling depth
External diameter	Outer diameter of cylindrical sampler body	Provides stability during penetration
Chamber capacity	Internal volume of the sample holding cavity	Determines amount of collected material
Penetration head geometry	Shape of the front cutting surface	Influences penetration efficiency

Different assembly configurations of the sampler were considered in order to examine its adaptability for various exploration depths. By increasing the number of cylindrical segments, the total length of the sampler could be extended. This flexibility allows the device to be used for shallow soil sampling as well as deeper subsurface exploration. Representative assembly configurations used during conceptual evaluation are presented in Table 3.

Table 3: Representative assembly configurations used during conceptual evaluation

Number of segments	Approximate exploration depth	Typical application
Two segments	Shallow depth investigation	Surface soil sampling
Three segments	Moderate depth exploration	Geotechnical site investigation
Four segments	Intermediate depth exploration	Subsurface characterization
Five or more segments	Greater exploration depth	Mining or deep investigation

The operational sequence followed during sampling was also defined to ensure reproducibility of the procedure. The sampler was first assembled using the required number of cylindrical segments. The assembled device was then connected to a driving rod and positioned vertically on the ground surface. Axial force was applied to penetrate the ground while fragmented material entered the internal chamber. After the desired depth was reached, the sampler was extracted, and the segments were separated sequentially to recover the collected sample. The operational procedure is summarised in Table 4.

Table 4: Operational procedure

Step	Procedure	Purpose
1	Assemble required number of cylindrical segments	Adjust device length according to exploration depth
2	Connect sampler to driving rod	Transfer penetration force
3	Apply axial force to penetrate ground	Collect soil or rock fragments
4	Extract sampler from ground	Retrieve device after penetration
5	Separate segments and access chamber	Recover collected samples

The conceptual evaluation also considered operational advantages related to maintenance and field handling. Unlike rigid samplers where damage to a component may require replacement of the entire tool, the modular system allows individual segments to be replaced independently. This feature may reduce equipment downtime and maintenance costs during exploration activities. The comparative operational characteristics between modular and conventional sampling systems are summarised in Table 5.

Table 5: The comparative operational characteristics between modular and conventional sampling systems

Parameter	Conventional sampling tool	Modular multi segment sampler
Structural configuration	Single rigid body	Multi segment assembly
Adaptability	Fixed length	Adjustable length
Maintenance	Replacement of entire tool	Replacement of individual segment
Transport	Difficult for long tool	Segmented transport
Field handling	Limited flexibility	High operational flexibility

Certain assumptions were considered during the conceptual design stage. The device was assumed to operate in soil and weak rock formations where penetration through axial force is feasible. The evaluation was limited to conceptual modelling and operational procedure analysis. Prototype fabrication and field testing were not included in this stage of the study. These assumptions are summarised in Table 6.

Table 6: Assumptions considered during the conceptual design stage

Assumption	Description
Ground condition	Soil or weak rock formations suitable for penetration
Loading condition	Predominantly axial penetration force
Device operation	Manual or mechanical driving mechanism
Study scope	Conceptual development and operational evaluation

3. RESULTS AND DISCUSSION

The development of the modular multi-segment rock soil sampler resulted in a structurally integrated system capable of adapting to different subsurface exploration requirements. The conceptual modelling and structural evaluation confirmed that The assembled device maintained axial alignment along the length of the sampler. The cylindrical segments formed a continuous structural body once connected through the segment interfaces, allowing penetration forces to be transmitted effectively from the driving rod to the penetration head. The overall configuration demonstrated that the modular approach can maintain structural stability while allowing flexible adjustment of the sampler length according to investigation depth.The penetration head geometry was designed to concentrate the applied force at the ground interface. The modelling assessment indicated that the cutting configuration provided multiple contact points with the soil or weathered rock surface. This arrangement may facilitate fragmentation of compact material during penetration and assist in directing the generated particles toward the sampling chamber. The front cutting section, therefore plays an important role in improving the entry of the device into the ground while maintaining the structural continuity of the sampler body. The functional behaviour of the penetration head and the structural body is summarised in Table 7.

Table 7: The functional behaviour of the penetration head and the structural body

Parameter	Observation from evaluation	Engineering implication
Penetration head configuration	Multiple cutting edges at contact surface	Facilitates fragmentation of compact material
Structural body alignment	Continuous cylindrical alignment of segments	Enables effective transfer of penetration force
Segment interface stability	Secure attachment between adjacent modules	Prevents displacement during operation
Sampler integrity	Stable structural configuration during penetration	Supports reliable sampling process

The connection mechanism between individual segments also demonstrated effective mechanical stability during assembly evaluation. Each segment interface-maintained alignment along the central axis of the sampler and prevented rotational displacement between adjoining sections. This behaviour ensured that axial penetration forces were distributed along the full length of the assembled structure. In conventional rigid samplers, the structural body is manufactured as a single piece, which restricts flexibility during field operations. The modular design allows the number of segments to be adjusted depending on the exploration requirement while maintaining structural continuity. The observed performance of the connection interfaces is presented in Table 8.

Table 8: Observed performance of the connection interface

Performance aspect	Conventional sampler	Modular multi segment sampler
Structural configuration	Single rigid body	Multi segment structure
Segment connection	Permanent	Detachable connection interface
Structural adaptability	Fixed length	Adjustable assembly
Maintenance approach	Entire tool replacement	Individual segment replacement

The sampling chamber incorporated within the device also demonstrated effective functionality during conceptual evaluation. The chamber was positioned behind the penetration head so that fragmented soil or rock material generated during penetration could enter the internal cavity of the sampler. The cylindrical chamber geometry provided sufficient storage space for collected material within a single penetration cycle. The enclosed cavity also reduced the possibility of sample loss during retrieval of the sampler from the ground. Access to the chamber was achieved by sequentially separating the cylindrical segments after extraction of the device. The operational characteristics of the sampling chamber are summarized in Table 9.

Table 9: Operational characteristics of the sampling chamber

Feature	Observed behaviour	Functional advantage
Chamber location	Positioned behind penetration head	Allows direct entry of fragmented material
Chamber geometry	Cylindrical internal cavity	Provides storage capacity for samples
Retrieval access	Achieved through segment separation	Enables easy extraction of collected material
Sample retention	Enclosed internal cavity	Reduces sample loss during retrieval

The modular configuration also demonstrated significant advantages in terms of adaptability during subsurface exploration. The total length of the sampler could be adjusted by varying the number of cylindrical segments used in the assembly. This feature allows the device to be configured for shallow investigations as well as deeper subsurface sampling without requiring multiple separate tools. The segmented structure also improves transportation efficiency because the device can be transported as individual components rather than a single rigid tool. The adaptability characteristics of the sampler are summarised in Table 10.

Table 10: Adaptability characteristics of the sampler

Operational parameter	Conventional sampling tools	Modular multi-segment sampler
Sampling depth adjustment	Not possible	Achieved by a varying number of segments
Equipment transport	Difficult for long, rigid tools	Segmented components easily transported
Field assembly	Not required	Assembly is possible according to the exploration depth
Operational flexibility	Limited	High flexibility

The results obtained from the conceptual evaluation highlight the potential benefits of adopting a modular design for subsurface sampling devices. The ability to assemble the sampler using different numbers of segments provides a practical solution for field investigations where exploration depths vary across different locations. In addition, the detachable structure simplifies equipment maintenance because damaged components can be replaced individually without discarding the entire assembly. This feature may reduce operational downtime during geotechnical investigations and mining exploration activities.

Another important observation relates to the handling and deployment of the sampler during field operations. The segmented configuration allows easier transportation and storage compared with conventional rigid samplers that may be difficult to transport over long distances or rugged terrain. The modular system therefore offers advantages not only in structural adaptability but also in operational logistics.

Although the conceptual evaluation demonstrates several advantages of the proposed sampler, experimental validation is required to fully assess its performance under real ground conditions. Future studies should focus on prototype fabrication and controlled laboratory or field testing to evaluate penetration efficiency, durability of the segment interfaces, and the quality of collected samples. Such investigations will provide quantitative data on the operational performance of the modular multi segment rock soil sampler and its suitability for practical geotechnical exploration applications.

4. CONCLUSION

The present study described the development of a modular multi segment rock soil sampler intended to improve adaptability during geotechnical exploration. The conceptual design integrated a penetration head, sequential cylindrical segments, a sample holding chamber, and a base connection unit that allows attachment to driving equipment. The modular configuration enabled the sampler to be assembled using different numbers of segments, which allows the overall length of the device to be adjusted according to the required exploration depth. This flexibility addresses a major limitation of conventional rigid sampling tools that are manufactured with fixed structural lengths.

The structural evaluation indicated that the connected segments maintained axial alignment and provided a continuous path for the transmission of penetration forces from the driving rod to the penetration head. The penetration head geometry was designed to facilitate entry into soil or weathered rock formations while directing fragmented material toward the internal sampling chamber. The enclosed chamber allows temporary storage of collected material until the sampler is retrieved and disassembled.

The modular configuration also offers practical advantages in terms of equipment handling, transportation, and maintenance. Individual segments can be transported separately and assembled at the investigation site, which simplifies logistics during field exploration. In addition, damaged segments can be replaced independently without requiring replacement of the entire sampler assembly.

Overall, the developed sampler demonstrates potential advantages for subsurface investigations where variable exploration depths and operational flexibility are required. Future research should focus on prototype fabrication and experimental testing to evaluate penetration efficiency, durability of segment connections, and the quality of collected samples under field conditions. Such investigations will help establish the practical applicability of the modular multi segment rock soil sampler for geotechnical and mining exploration activities.

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