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The GP sampler: a new innovation in core sampling

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ABSTRACT: This paper introduces a new type of sampler called the GP sampler. It was designed to sample gravelly soils, but has proven to be successful in sampling soils ranging from dense sand, to gravel, as well as sedimentary rocks. The sampler is constructed of a single core barrel and uses a viscous polymer gel as its drilling fluid. The polymer plays a key role in obtaining high-quality samples, helping to preserve the soil structure. The polymer gel was also employed in more traditional style samplers, in an effort to improve the quality of samples obtained from silt, silty sand, and sand. In the field, GP samplers have been successful where other conventional methods have experienced difficulties or failed altogether. Although the GP sampler is not a perfect sampler, it is beginning to make a qualitative difference in the sampling of granular soils for engineering analyses.

1 INTRODUCTION

In geotechnical site investigation, obtaining a high quality sample of granular soils is one the most difficult tasks, principally because the very process of sampling can easily disturb the soil. During the late 1990s, the Japanese geotechnical consulting company, Kiso-Jiban Consultants, developed a new type of sampler called the GP sampler. This innovative sampler was designed specifically to overcome the limitations of prevailing sampler methods: to obtain high-quality samples of sands and gravels, without freezing and without the typical disruptive impact to the integrity of the sample.

The name GP is an abbreviation for Gel Push. The sampler uses a very thick polymer gel or solution as its drilling fluid, as well as for a lubricant. Unlike conventional drilling fluid, the polymer solution is not circulated; it is simply pushed out of the sampler tube or barrel to remove the cuttings, cooling the bit and protecting the sample as it enters into the sampler. Thus, the name Gel Push or GP has been adopted.

The sampler design was completed in 2010. This produced four variations of GP samplers, each specifically useful for a particular sampling requirement: GP-Rotary, GP-Drilling, GP-Triple, and GP-Static. They will be referred to as GP-R, GP-D, GP-Tr, and GP-S in the rest of the text. Table 1 summarizes the principal features of each one of the GP samplers.

The GP-R sampler is a single core barrel sampler

Table 1. Summary of GP samplers.

	GP-R	GP-D	GP-Tr	GP-S
Sampler configuration	single core barrel	single core barrel	modified triple tube sampler	modified Osterberg sampler
Bit type or shoe	impregnated diamond bit	impregnated diamond bit	shoe with metal bit for overcoring	shoe
Function of polymer	Non-circulating drilling fluid for carrying cuttings, cooling the bit and protecting the cored sample.	Non-circulating drilling fluid for carrying cuttings, cooling the bit and protecting the cored sample.	Reducing friction between the cored sample and sampler wall.	Reducing friction between the cored sample and sampler wall.
Special features	Electric motor is used for coring.	Electric motor is used for coring. Fitted with core lifter.	Polymer dispensing ring is fitted.	Core catcher dispenses the polymer and retains cored sample.
Ground suited for sampling	dense sand, gravel, and sedimentary rock.	dense sand, gravel, and sedimentary rock.	medium to dense sand and sand with gravel.	silt, silty sand, and loose sand.
Typical core diameter (mm)	100, 150, 200, and 300	100, 150, and 200	83	75
Maximum sample length	1 m	1 m	1 m	1 m

with very simple construction. It has proven successful in obtaining high-quality samples of sands, gravels, and sedimentary rocks. The sampler's flexibility in accommodating a wide range of formations is one of its attractive features.

While the GP-R sampler was designed for sampling at the ground surface, or from an excavated trench, the GP-D sampler was developed in order to conduct equally high-quality sampling in boreholes. It has the same basic construction as the GP-R, but is fitted with a special "catcher" mechanism that enables it to retain the core inside the sampler during retraction from the ground and borehole.

The GP-Tr and GP-S samplers were designed around a rotational triple tube sampler and the Osterberg sampler, respectively. They both use the highly viscous polymer solution to reduce friction between the cored sample and sampler tube wall, minimizing one of the primary causes of sample disturbance.

The basic design of the four GP samplers, their operating procedures, and several case records of actual site investigations are described in this paper. GP samplers have proven to be successful in obtaining samples at formations where sampling had previously not been possible, or was otherwise difficult to accomplish through conventional means. Furthermore, this paper illustrates the impact and contributions these innovative samplers have made in site investigation.

2 THE GP-R SAMPLER

The GP-R sampler was originally designed for sampling gravel formations at the ground surface. It was the first GP sampler built and its successful use of the GP technology made it the archetype of the line of GP samplers that followed. Foundational to this technology is the more than 30 years of experience in sampling held by the engineers responsible for its development. In this section, the design and operation of the GP-R sampler, the behavior characteristics of the polymer solution, and two case records of site investigations are included.

2.1 *The design and operation of GP-R sampler*

The GP-R sampler is a single core barrel sampler, available in barrel diameters of 100 mm, 150 mm, 200 mm, and 300 mm. Figure 1 depicts a GP-R sampler with the sample having entered about one-third of the way into the core barrel. Prior to drilling, the ground surface is prepared by the addition of a thin layer of cement mortar, which is shown in Figure 1. This layer assures the smooth start of the drilling and minimizes disturbance to the ground below. The sampler barrel is filled with a thick polymer solution and placed at the ground surface. As the barrel is turned and pushed downward, an impregnated diamond bit cuts into the ground. This specific bit is smooth to the touch and grinds through granular soils and other ground formations with minimum disturbance. The sample core, with its mortar cap, is forced into the barrel as the sample cuts it from the surrounding soil, pushing the stored polymer solution up, and squeezing it over and around the core into an annular space of about 1 mm between the core and the barrel wall.

The polymer utilized in this process is a commercially available product, and is commonly added to traditional drilling fluid to increase its viscosity. Unlike the prevailing drilling fluid, the polymer solution used in all the GP sampling is highly concentrated with a 2.5 to 4 % ratio of polymer to water. This creates a fluid whose viscosity is more than ten times thicker than the industry norm of 0.1 to 0.4 % concentration and takes full advantage of the polymer's non-Newtonian fluid characteristics. The polymer solution is very thick and viscous when it is still, but becomes more fluid-like when it is sheared. This behavior is known as "shear-thinning".

During the sampling process, the barrel rotates at 300 to 800 rpm depending on the size of the barrel. Smaller barrels need to rotate faster to attain the desired linear cutting speed. The polymer solution flowing alongside the barrel wall in the annular space is sheared by the high rotational speed and loses viscosity. This zone of low viscosity polymer solution acts like a protective membrane, isolating the cored sample from the barrel's rotational motion.

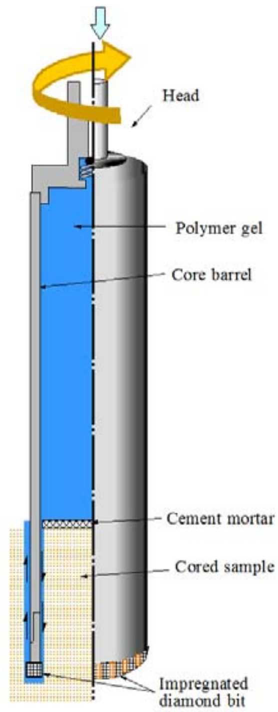

Figure 1. Cross-section of GP-R sampler with cored sample entering into the sampler barrel.

Unlike conventional drilling fluid, which tends to wash out fine particles, the polymer solution's high viscosity and slow flow rate leave the fines undisturbed. Since the fines act as a matrix material, holding the coarser particles or gravels in place, sample disturbance during the polymer gel sampler coring is kept to a minimum. The sheared solution essentially seals the cored sample as it flows downward to exit the barrel at and around the bit, cooling the bit and carrying away the cuttings as it passes out of the barrel into the borehole. Further details of the polymer characteristics are discussed in sub-section, 2.2.

Figure 2 shows the operating sequence of GP-R sampling from start to finish. When the coring is completed the excess polymer gel is extracted, the ground adjacent to the barrel is excavated, and a wedge is then driven under the barrel to separate the core sample from the ground. It is then a simple procedure to obtain the sample. Figure 3 shows the photos of a coring operation at a pit, driving a wedge, and trimming the ends of the sample which is at the laboratory for testing. The circular saw in the photo has an impregnated diamond cutting edge and is lubricated by the GP formulated polymer solution.

A beneficial feature of both the GP-R and GP-D samplers is their use of an electrically powered motor for coring. The motor can be preprogrammed to precisely control the sampler's rotational speed and penetration rate. In stark contrast to the oscillation caused by diesel motors, the electric motor produces very little vibration and consequently, significantly less disturbance to the sample and the subject soil.

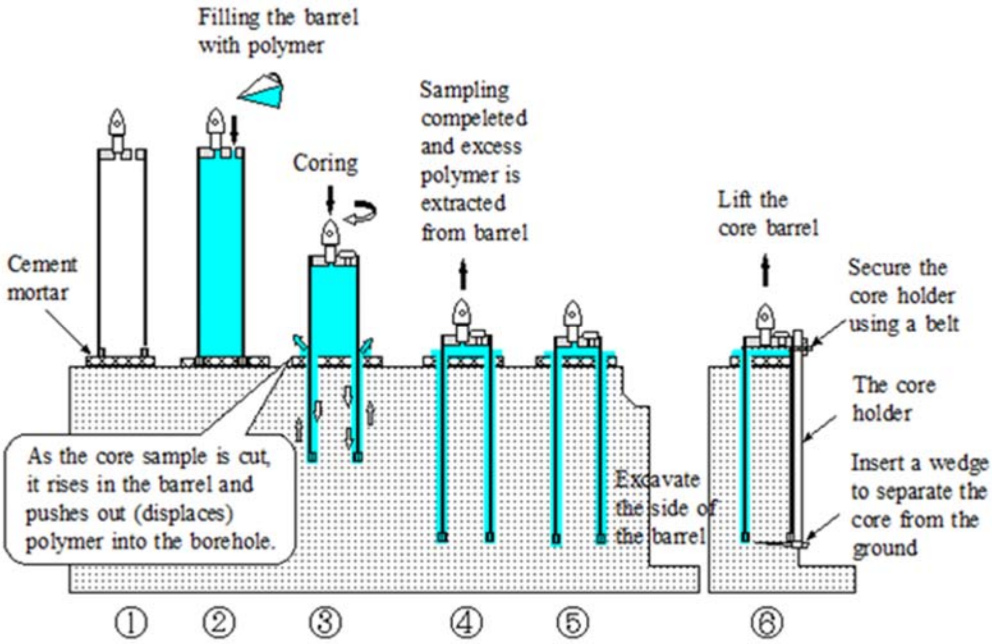

Figure 2. Operating sequence of GP-R sampling on the ground surface.

(a) Coring using electric motor. (b) Inserting a wedge. (c) Trimming the ends.

Figure 3. GP-R sampling on the ground surface at a trench pit, and trimming the ends in the laboratory.

This results in a smoother core sample, leaving a cleaner cut face and allowing for multiple samples to be extracted in close proximity, increasing sampling efficiency. Because of the relative ease and compactness of the GP-R's operation, sampling may be conducted in trenches, excavation pits, inside tunnels, or at the bottom of deep wells. Additionally, as many samples as are needed may be economically obtained from the same location.

Figure 4 shows the first GP-R sample obtained from the commercial use of a GP sampler. The site was an artificially compacted fill for the construction of highway facilities. All the gradation curves obtained at the site are shown in Figure 5, and reveal a ground consisting mostly of gravel with the maximum size ranging from 50 to 100 mm. The seismic stability of the fill was under investigation, and due to the maximum size of the gravel at the site investigated being around 50 mm, the 300 mm diameter GP-R sampler barrel was used. In line with the industry practice of a particle size to core diameter ratio of five to one, the choice of the 300 mm barrel to obtain samples was appropriate to ensure accurate testing of the fill.

The GP-R sampler was initially developed for sampling gravelly soils, but it can accommodate a broad range of soils from sands to gravels, and even soft rocks. Figure 6 shows examples of a variety of cored samples obtained by GP samplers.

Figure 4. The first GP-R sample obtained.

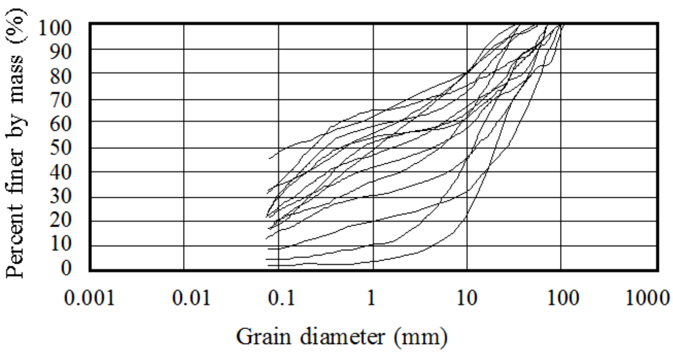

Figure 5. All the gradation curves obtained at the site (Abe et al. 2002).

Sample core of mudstone (GP-R: 200 mm).

Sample core of gravels suspended in a matrix of dense sand (GP-R: 300 mm).

Dense sand sample core (GP-D: 200 mm).

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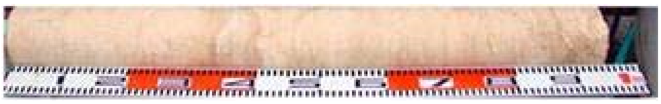
Sample core of fragmented shell in dense sand (GP-D: 200 mm).



Sample core of coral limestone (GP-D: 100mm).

Figure 6. Wide range of rocks and soils sampled by GP samplers.

2.2 *Polymer characteristics and its functions*

Since the polymer solution plays a vital role in GP sampling, a description of the general characteristics of the polymer is given in this sub-section. Some characteristics unique to the polymer solution used in GP sampling are also addressed. The basic polymer is a partially hydrolyzed polyacrylamide and is commonly called PHP polymer. It is readily available throughout the world, but the viscosity characteristics vary depending on the manufacturer.

The polymer characteristics discussed here are those of a product locally available in Japan and may not apply to PHP polymers produced elsewhere. The polymer is sold in liquid form dissolved in mineral oil. The concentration of polymer solution referred to in this text is measured in the weight percentage of commercially sold polymer to the water it is mixed with.

Figure 7 shows the viscosity of the polymer solution having concentrations ranging from 0.1 to 5.0 %. Viscosity is measured by a viscometer, which rotates at different speeds. It is clear from Figure 7 that the higher the concentration and slower the rotation of the viscometer, the higher the viscosity, and vice versa.

GP sampler barrels typically rotate at a viscometer rotation equivalent of 8000 rpm, or the zone indicated by the letter A in Figure 7. Thus, from still to the barrel's full rotational speed, the polymer's viscosity drops to about one ten-thousandths of still state. Since the viscosity of water is about 1.0 mPa・s, the polymer is still viscous enough to maintain laminar flow, even when the barrel is rotating at full speed, yet fluid enough to isolate the barrel's rotational motion, preventing it from being transmitted to the cored sample. To achieve these favorable conditions, there is a delicate balance that must be maintained between the concentration of the polymer solution and the speed at which the barrel rotates.

Figure 8 illustrates the different behaviors of drilling solutions. Presented are three buckets, each containing one of these solutions, respectively, being mixed with an electric blender; 3.0 % polymer concentration, 0.3 % polymer concentration, and conventional drilling fluid. The polymer solution of 3.0 % climbs up along the mixing rod as if long polymer chains are being curled up. The effect of the polymer solution rising up, as shown in Figure 8 is called the Weissenberg effect. This effect is known to generate inward normal stress, which can act to hold the cored sample together inside the GP

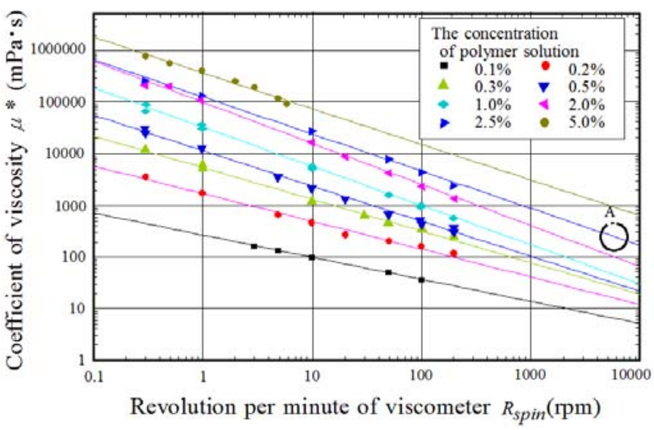


Figure 7. Viscosity of polymer solution at different concentrations (Yanagisawa et al. 2003).

(a) 3.0 % polymer (b) 0.3 % polymer (c) drilling fluid

Figure 8. Polymer behavior at different concentrations and conventional drilling fluid.

barrel. The bucket filled with a 0.3 % solution shows only a very faint rise, indicating a thin polymer solution will be much less effective at protecting the cored sample. The bucket with the conventional drilling fluid shows it behaving like an ordinary fluid, displaying none of the advantageous characteristics of the GP polymer solution.

Figure 9 shows an apparatus built to simulate the GP-R and GP-D coring samplers. A stationary metal tube representing the cored sample, being 100 mm in diameter, with load cells mounted on its sides to measure shear and normal stresses, was placed at the center of the apparatus. A slightly larger tube, representing the barrel, and having a diameter 2 mm wider than the first, was placed over the stationary tube. The annular space was then filled with a 2.5% concentration polymer solution and confining pressures of 100 and 149 kPa were applied. The outer tube was rotated from still to 400 rpm and then returned to still. Figure 10 shows the normal and shear stresses

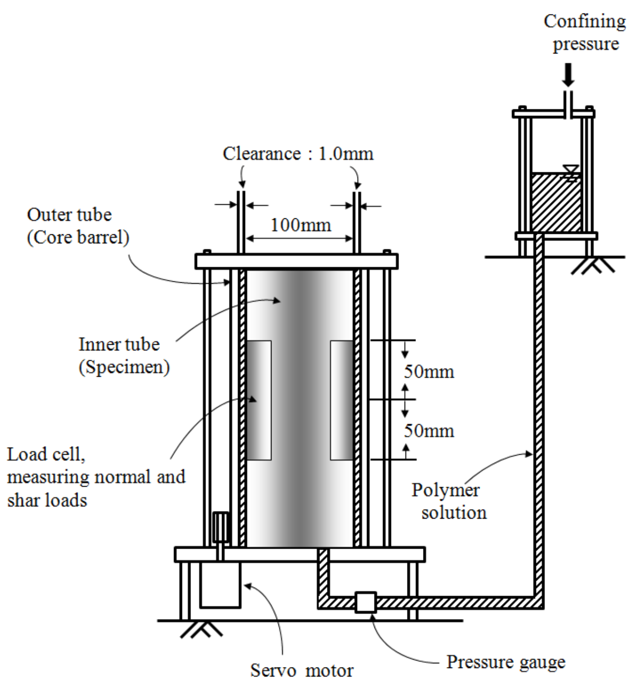
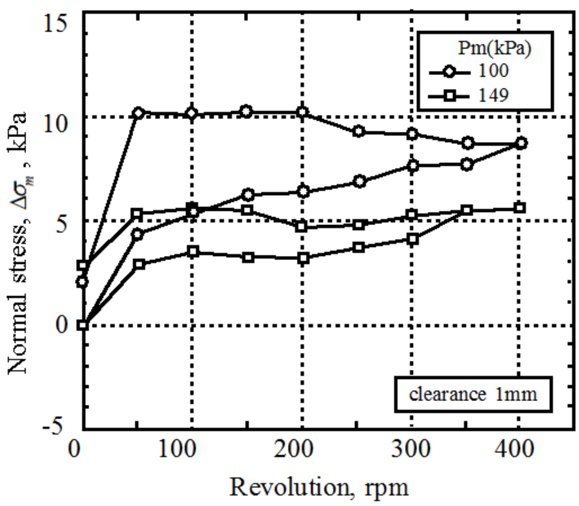


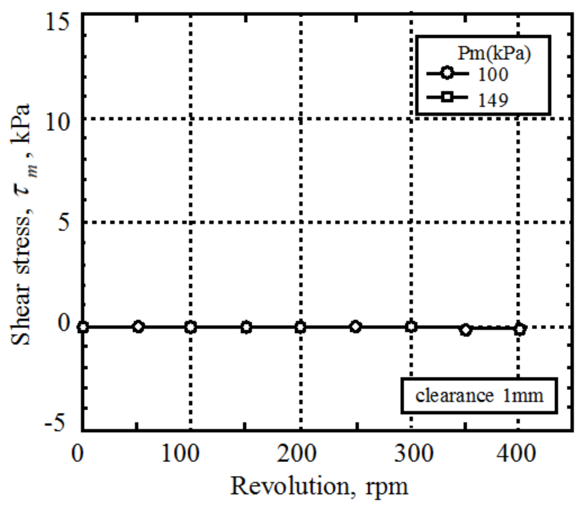
Figure 9. An apparatus simulating GP-R and GP-D coring (Yanagisawa et al. 2004).

measured at different rotational speeds. As is evident from Figure 10, normal stress builds up steadily until the revolutions reach 100 rpm, and then the stress becomes stable. Interestingly, a small normal stress remains even after the barrel comes to a stop. This is likely to be the normal stress generated by the Weissenberg effect. On the other hand, the shear stress measurements showed no increase at all during the entire test, indicating that a very narrow annular space of 1mm, filled with the polymer solution, is enough to isolate the cored sample from the rotational motion of the barrel.

With the GP-Tr and GP-S samplers, the polymer solution is used differently from the GP-R and GP-D samplers. As will be discussed in Sections 4 and 5, these samplers behave very much like conventional samplers, with the sample coming into direct contact with the sampler wall. However, the same thick polymer solution is employed to decrease the resulting friction, which is a major cause of sample disturbance in conventional methods.



(a) Normal stress vs. revolution.



(b) Shear stress vs. revolution.

Figure 10. Normal and shear stresses measured on a tube simulating cored sample (Yanagisawa et al. 2004).

In order to estimate the effectiveness of the polymer as a lubricant, a series of tests were carried out. River sand was compacted inside test tubes, forming samples each 30 cm in length, with a density of 14 kN/m^3 and having a moisture content of 14 %. A hydraulic piston was used to push the compacted soil out of the tubes. Figure 11 shows the thrust force needed to extrude each sample.

Both thin wall stainless steel and PVC tubes were used for this test; their inside diameters being 70 mm and 83 mm, respectively. It is clear that the stainless steel tubes exhibited significantly more friction as compared to the PVC tubes. The lower friction of the PVC tubes may be attributable to the material’s smooth surface and flexibility to expand, both of which reduce stress build-up.

Figure 11 also shows the thrust force needed to eject soil samples from the stainless steel tubes, each of which had been either coated with polymer or lined with Teflon. Both surface treatments were equally effective in significantly reducing the friction between the sample and the sampler wall. This property lends further support to the use of the polymer enhanced samplers, as it produces a very low friction environment for the sample to enter into the collection tube. It also significantly reduces the force needed to extrude a cored sample out of the tube, whether in situ or in the laboratory.

It should be noted that in the course of the design of the GP Sampler, Professor Tani, of Yokohama National University, along with his research group, conducted extensive studies on the polymer behavior. Their work made a significant contribution to the development of the GP samplers and the unique use of the high viscosity polymer to obtain a reliably superior core sample (Tani et al. 2004, 2006, Yanagisawa et al. 2003, 2004, Kaneko et al. 2005, Shirai et al. 2004, Ishizuka et al. 2010).

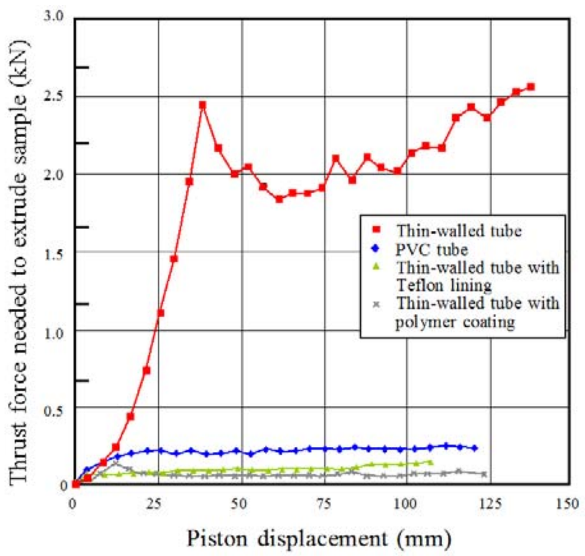


Figure 11. Thrust force needed to extrude soil sample out of various sampler tube configurations.

2.3 *A site investigation at Yui landslide site*

Yui is located along the Pacific coast of Shizuoka Prefecture, between Tokyo and Nagoya, and situated south-southwest of Mount Fuji. The hillside of Yui hangs over the narrow coastline making the area picturesque. However, the hillside presents a serious landslide hazard to three of Japan's major transportation arteries: the Tomei Expressway; the Tokaido Line of Japan Rail; and the National Route One. They are all located just underneath the hill as shown in Figures 12(a) and (b).

The hillside experienced a number of slides in the past which negatively affected the traffic flow of the three arteries. Specific slides were caused by either heavy precipitation or by earthquake activity. The site is located along the coast of the Suruga Bay where the Sagami Trough runs north to south. The trough, which is capable of generating an earthquake with a magnitude in excess of 8, makes the area's seismic stability of principal concern.

Figure 13 shows four potential landslide zones at the Yui site. These zones are referred to as Blocks. They include the Yamanaka Block, the Hachigasawa Block, the Ohkubo Block and the Ooshi Block. All the data presented in this section was made possible with the consent of Mt. Fuji Sabo Office, Chubu Regional Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism.

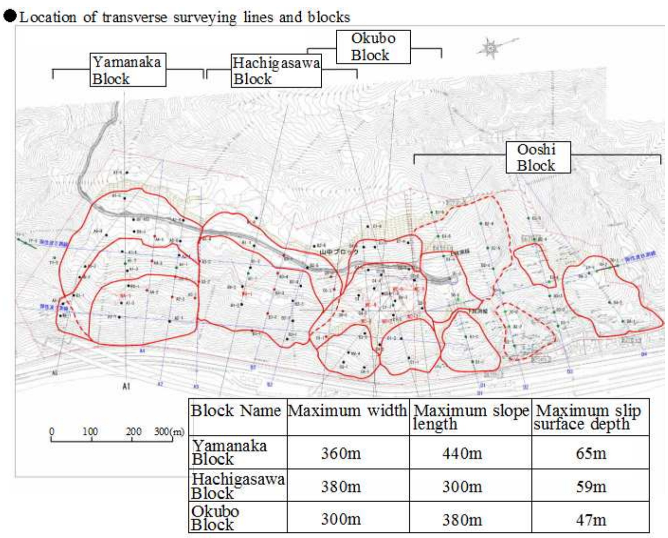
In 2005, a comprehensive investigation was conducted at the site, followed by the necessary mitigation work. GP-R sampling was carried out as a part of the geotechnical site investigation. Sampler barrels 200 mm in diameter were used at the Yui site. At the time of the GP-R sampling work, some of the deep drainage wells for groundwater were still under construction. Using these wells, GP-R sampling was conducted at various depths, ranging from the ground surface to a depth in excess of 50 m underground.

Figure 14 shows a cross section of Ohkubo Block. It indicates that several slip surfaces have been identified from previous investigations. GP-R sampling was carried out at one of the drainage wells in the center of the slope, near the location shown as site in Figure 14. At the actual drainage well site, the slip surfaced appeared closer to the ground surface than shown in Figure 14. Figure 15 is a photo of GP-R sampling work being done inside the well. Figure 16 shows the photos of the GP-R samples obtained at Ohkubo Block at the ground surface, as well as depths of 18.5 m, 27 m, and 29.5 m. Also seen in the figure, is a photo taken of the grounds after the samples were removed. One of the amazing features of the sampler is that it not only obtains high-quality samples, but the precision of the coring method leaves behind a beautifully excavated

(a) Yui site overview.

(b) Yui site looking from south.

Figure 12. Photos of Yui site (Mt. Fuji Sabo Office Homepage).



Block Name	Maximum width	Maximum slope length	Maximum slip surface depth
Yamanaka Block	360m	440m	65m
Hachigasawa Block	380m	300m	59m
Okubo Block	300m	380m	47m

Figure 13. Four slide blocks at Yui site (Mt. Fuji Sabo Office Homepage).

surface, which facilitates the visualization of the site soil formation. Here, it can clearly be seen that below the depth of 27 m, the formation changes to more solid sedimentary rocks.

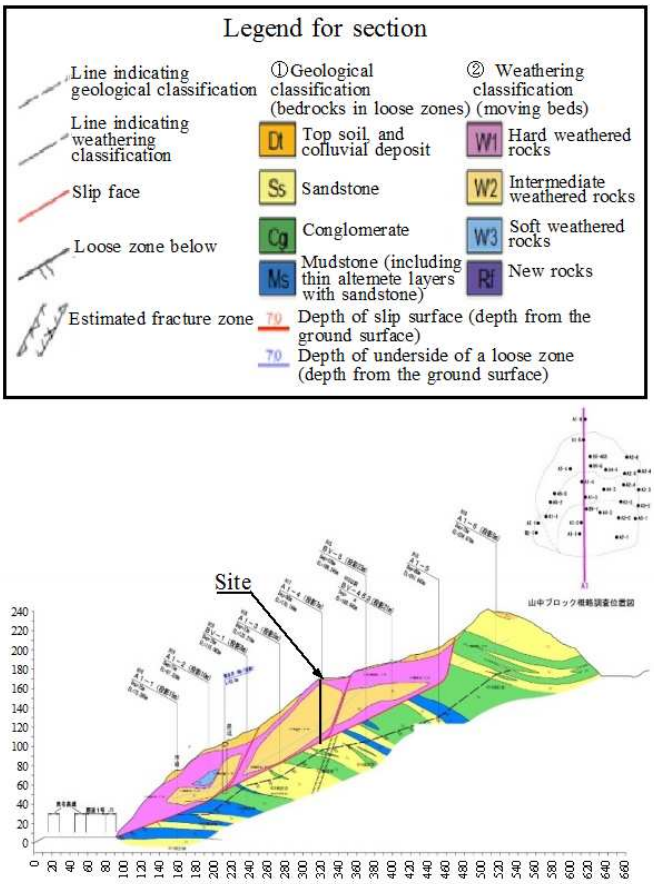


Figure 14. Cross-section at Ohkubo Block, Yui (Site location is marked on a cross-section made available in Mt. Fuji Sabo Office Homepage).

Figure 15. Photo of GP-R sampling inside the deep well at Ohkubo Block (Supplied by Mt. Fuji Sabo Office).

(a) Ground surface.

(b) At depth of 18.5 m.

(c) At depth of 27 m.

(d) At depth of 29.5 m.

Figure 16. Photos of GP-R samples obtained at Ohkubo site at four depths and the excavated surfaces (Supplied by Mt. Fuji Sabo Office).

At Hachigasawa Block, the GP-R sampler captured a slip surface in a core sample taken at a depth of 42 m, as shown in Figure 17. It is quite rare to be accorded the opportunity to view a slip surface, captured in a core obtained at depth, at such close proximity.

At the Yui site, the shear wave velocities measured in situ were compared with those of the GP-R samples in the laboratory. Figure 18 shows the ratio of the two shear wave velocities in the ordinate and the laboratory measured shear wave velocities in the abscissa for the samples obtained at depths of: 2.0 m, 13.0 m, 31.0 m, 46.5 m, and 52.0 m at Yamanaka Block. Judging from the shear wave velocities, the overall quality of the samples appeared very good, except for one data point having the shear velocity ratio falling below 0.8, which was considered too low for a high-quality sample. There seems to be a tendency for the quality of the sample to improve with increasing depth, as well as with increasing shear velocity.

Figure 17. A photo of suspected slip surface at Hachigasawa Block at a depth of 42 m (Supplied by Mt. Fuji Sabo Office).

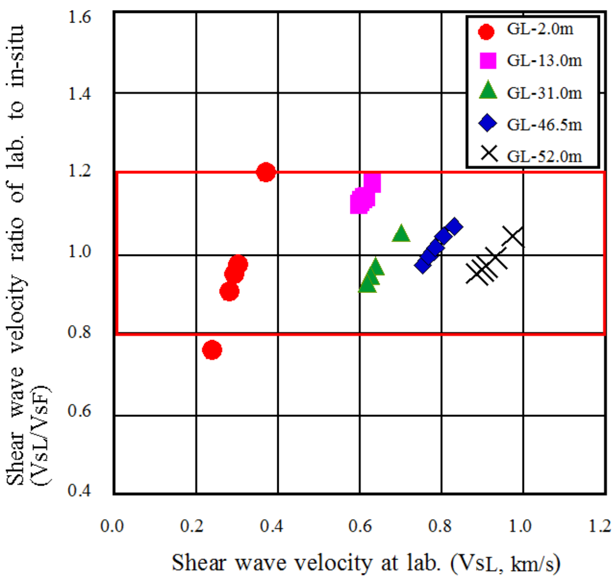


Figure 18. Shear wave velocity ratio of laboratory to in-situ vs. shear wave velocity at laboratory (Supplied by Mt. Fuji Sabo Office).

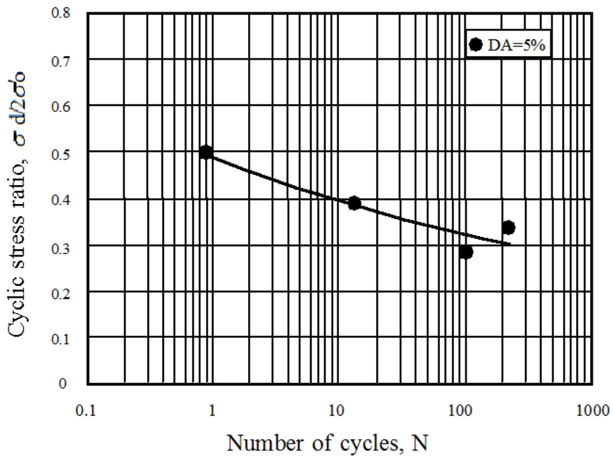


Figure 19. Relationship between cyclic stress ratio and number of cycles to cause DA=5% at Yamanaka Block (Supplied Mt. Fuji Sabo Office).

Undrained cyclic triaxial tests were carried out on GP-R samples obtained above the slip surface at Yamanaka Block to determine the liquefaction potential and deformation characteristics of the ground. Figure 19 shows the results of the test using the criteria of a double amplitude of 5 %, as the pore water pressures never reached the confining pressures.

The GP-R sampler performed admirably at the Yui site. High-quality samples were obtained and provided to the laboratory for testing to determine the seismic stability of the slope. Though not included in this report, static triaxial tests were also performed using GP-R samples. Furthermore, because 200 mm diameter samples were obtained, smaller specimens 80 mm in diameter were carved out from them, so that the general alignment of the formation coincided with the shear plane of the triaxial tests, to more accurately determine the strength of the formation. Last but not least, the samples provided incredible visual images of the site, contributing to a better understanding of its geology.

3 THE GP-D SAMPLER

The GP-D sampler is a single core barrel sampler that has been specifically engineered to operate in boreholes. The design of the sampler, operational procedures, and two cases of site investigation, carried out using the sampler, will be discussed in this section.

3.1 *Design and operation of the GP-D sampler*

The GP-D sampler has essentially the same construction as the GP-R sampler, as shown in Figure

20. Three features have been added to the GP-R so that it can operate in a borehole. These features are as follows: the introduction of a free piston, a core lifter, and a polymer solution supply connection at the sampler head.

The free piston serves as a plug at the bottom end of the barrel, and prevents the polymer solution from leaking out of the barrel while the sampler is being lowered down the borehole. Once the sampler is positioned on the bottom of the borehole, the barrel begins to rotate, cutting the sample. The free piston is pushed upwards by the entering core, forcing the polymer to flow into the annular space between the core and the barrel. Finally, it exits the barrel in the same way as in the GP-R sampling process, cooling the bit and carrying away the cuttings.

Since a wedge cannot be driven in the borehole to separate the core from the ground, a core lifter is fitted just above the bit to squeeze the core sample, holding it in the barrel as the sampler is raised from the borehole. The lifter mechanism is a circular band as shown in Figure 21(a). When the coring is completed, the sampler barrel is nominally lifted, still attached to the formation site, the core sample resists the pull, slumping down slightly, and dragging the core lifter with it. This triggers the core lifter mechanism, causing it to tighten around the cored sample, and enabling the sample to break free from the ground. Finally, with the sample secured, the GP-D barrel is raised to the surface for sample extraction.

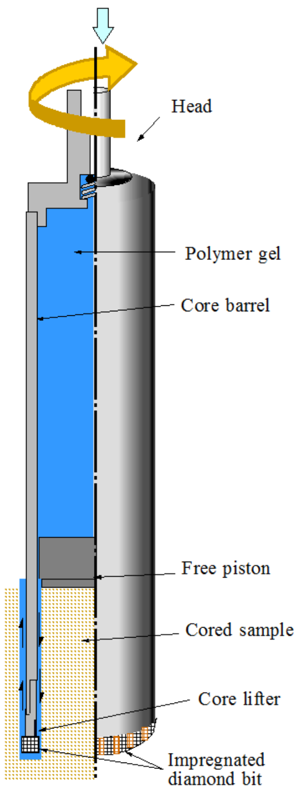


Figure 20. Cross-section of GP-D sampler with cored sample entering into the sampler barrel.

(a) Photo of core lifter.

(b) Photo of 200 mm GP-D sampler.

(c) Photo of GP-D sampling using an electric motor.

Figure 21. Photos of GP-D core lifer and sampling work.

The GP-D sampler barrel is available in diameters of 100 mm, 150 mm and 200 mm. The larger, 300 mm diameter sampler was not chosen for GP-D production as it would be excessively heavy to handle in borehole applications. Since the diameter of the sampler barrel is only 200 mm or less, the polymer stored in the barrel at the beginning of the sampling is not adequate to complete the drilling of a 1 meter long sample. Instead, the design of the GP-D sampler provides for the polymer solution to be continuously supplied through drill strings connected to the top of the sampler.

Figure 21(b) shows a 200 mm diameter GP-D sampler being lowered down into a casing for sampling. Figure 21(c) shows a foreman operating the 200 mm diameter barrel employing the same style electric motor as used with GP-R samplers. Since the GP-D sampler rotates at a very high speed, multiple centralizers are placed on the drill strings to ensure smooth, vibration free coring.

GP-D samplers are not bulky. As an example of the versatility of the GP-D sampler design, a very modest 100 mm diameter barrel sampler may be used inside a building as shown in Figure 22, where coring work is being carried out on the floor of a convenience store.

3.2 *A case of GP-D sampling at Site K*

One of the quandaries of sampling, especially with large diameter samples containing gravels or any other granular material, is the difficulty in verifying the quality of the samples obtained. It is extremely rare to know all the relevant parameters such as: in-situ density; the degree of cementation or aging; the way the granular particles are packed; past stress

Figure 22. Photo of GP-D sampling at a shop floor.

histories the ground has been subjected to; etc. It is generally accepted that if shear modulus or shear wave velocities in situ agree reasonably well with those measured in the laboratory, then the samples are considered to be of good quality. Another parameter that can be used to evaluate the sample quality is void ratio.

In the 1980s, the Central Research Institute of Electric Power Industry conducted extensive studies on Pleistocene gravel formations at four locations identified as Sites A, K, T, and KJ. At all four sites, very extensive geotechnical investigation and testing programs were carried out. These included: SPT; seismic survey; conventional sampling; freezing sampling; static; and cyclic laboratory tests. Since the gravels at the four sites contained very little fines, the freezing method was well suited for obtaining high quality samples.

Kokusho et al. (1994), Tanaka et al. (1989), Kudo et al. (1991), and others have reported the details of these investigations. About a quarter century later, an occasion arose to conduct GP-D sampling at Site K. This presented a very rare opportunity to check the quality of GP sampling against the results of the freezing method.

Figure 23(a) shows the photo of freezing sampling performed over twenty-five years ago at Site K. The sampler used then was a specially designed, 300 mm diameter, triple tube sampler. Figure 23(b) is a photo of the GP-D sampling carried out in 2006. Figure 24(a) shows one of the frozen core samples obtained during the Central Research Institute of Electric Power Industry study in the 1980s. The drill bit used for the freezing sampling was an impregnated diamond bit. Figure 24(b) shows a photo taken in 2006 of the GP-D sampler's barrel, with its impregnated diamond bit, with the cored sample inside. The figure also shows the cored sample after it has been extracted from the barrel.

Figures 25(1), (2) shows the soil profile at the four original sites, including SPT N-values, and the locations where the frozen samples were obtained. Also shown in the figure, are the results of a large penetration test or LPT, this is a heavyweight version of SPT, which has been designed for gravel formations. It uses a hammer weighing 980 N, instead of the SPT's 622.3 N, and has a drop height of 150 cm instead of the SPT's 75 cm. Figure 26 shows the gradation curves of the gravels at the four sites resulting from these tests.

From the results of seismic surveys carried out at all four locations, shear modulus at small-strain were calculated and compared with the shear modulus determined in the laboratory using the frozen samples, as shown in Figure 27. It is clear from the figure that the shear modulus determined in the laboratory measured about 40 % less than those measured in situ. The reason for the laboratory determined small-strain shear modulus being consistently lower than

(a) Photo of freezing sampling.

(b) Photo of GP-D sampling

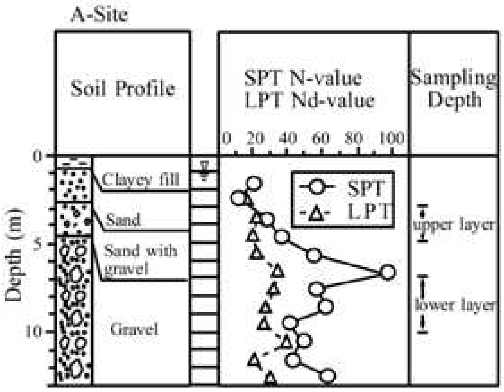
Figure 23. Photos of freezing and GP-D samplings at Site K.

the in-situ measurements may be attributed to some or all of the following causes: 1) freezing method can disturb the cored sample; 2) bedding error in laboratory testing; 3) small-strain shear modulus in the laboratory is not the same as in-situ determined modulus; and 4) anisotropy in the ground (Tanaka et al. 1998). At that time, conventional sampling without freezing was carried out at Site A, and the small-

(a) Photos of frozen core sample.

(b) Photos of GP-D sample.

Figure 24. Photos of frozen and GP-D samples obtained at Site K.



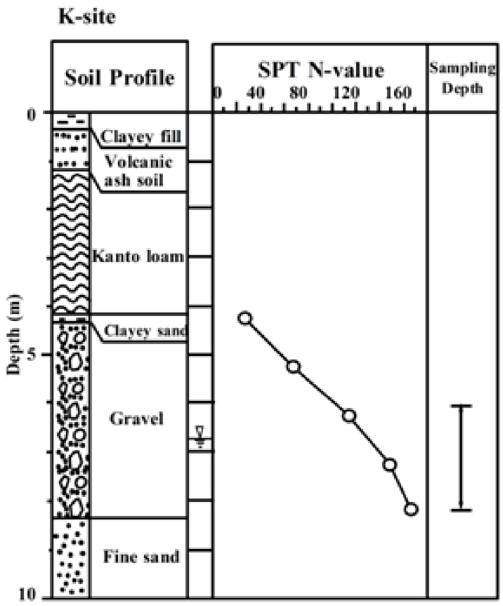


Figure 25(1). Soil profiles at A-site and K-site of four gravelly sites (Kokusho et al. 1994).

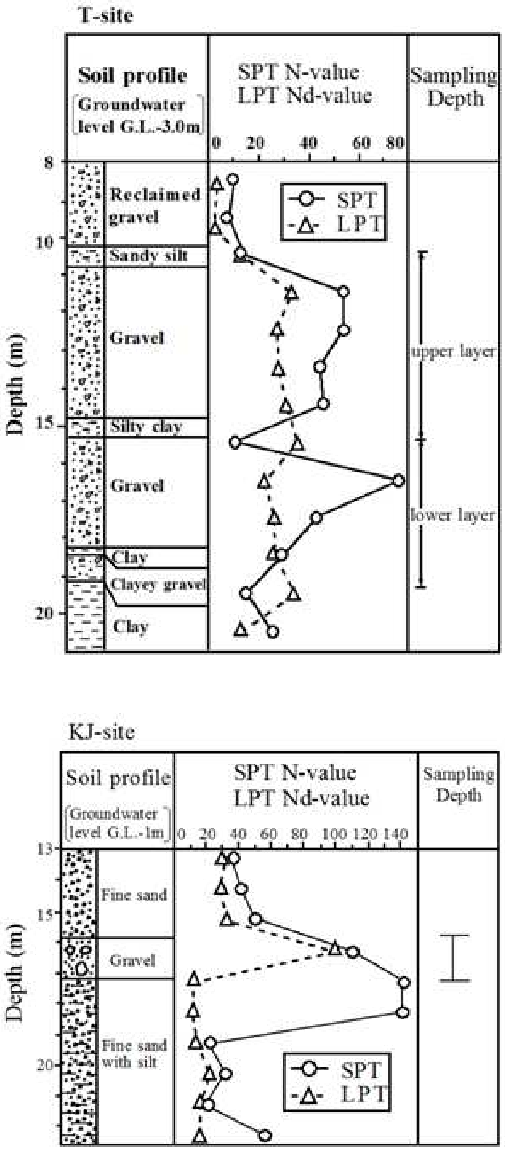


Figure 25(2). Soil profiles at T-site and KJ-site of four gravelly sites (Kokusho et al. 1994).

strain shear modulus determined from these samples showed even smaller values. The disturbance caused by sampling without the benefit of freezing was suspected to have severely loosened the pack of the cored samples.

In 2006, small-strain shear modulus of GP-D samples obtained at Site K were determined in the laboratory and compared with those of the frozen samples as shown in Figure 28. It is clear that the GP-D sample results align with those from the frozen samples, an indication that the GP-D samples are equal in quality to the frozen ones.

To further investigate the quality of GP-D samples, undrained cyclic triaxial tests were carried out to compare with the frozen samples, see Figure 29. Again, GP-D samples were in good agreement with the frozen samples. The average dry densities of the frozen and GP-D samples were 21.33 kN/m^3 and 21.51 kN/m^3, respectively. In the graph, one of the data points of the frozen sample plotted well below the others, indicating that the sample was very weak. The co-author of this paper was present on site for both the freezing and GP-D samplings and noticed the presence of underground water flow channels in some of the samples. These channels had formed where the fine particles, including sands, were carried away leaving only skeletal structures made of gravels. The weak sample contained such a zone. When tested in the laboratory, this type of zone breaks down easily under cyclic loading and falls low on the graph, as was suspected in this case. The average dry density of the frozen samples, excluding the weak sample was 21.53 kN/m^3, which is very close to that of GP-D samples, indicating the two sampling methods obtained samples with equivalent density.

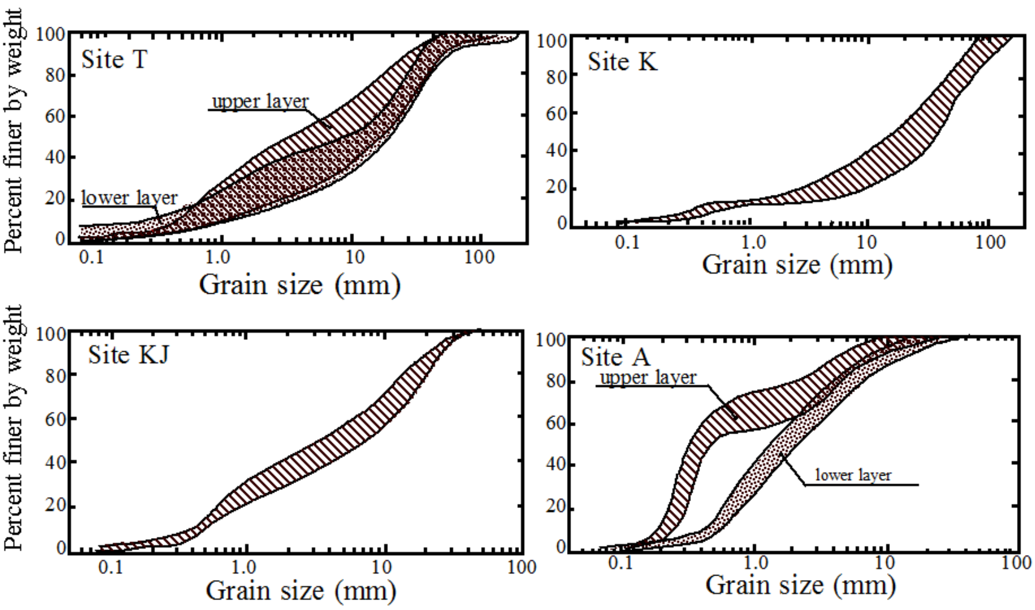


Figure 26. Grain size distributions of gravels at Sites T, K, KJ, and A (Kokusho et al. 1994).

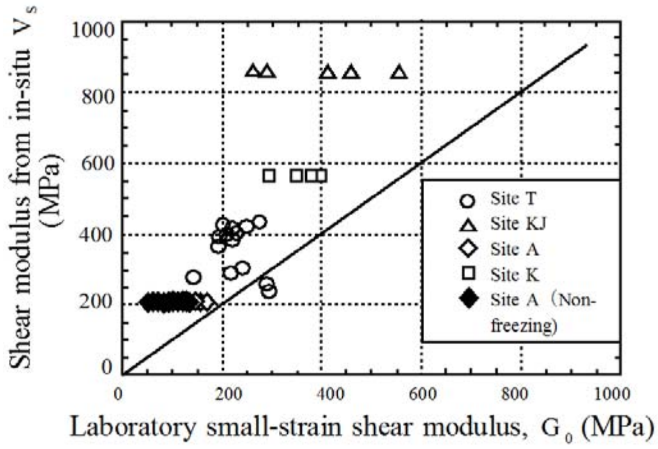


Figure 27. Comparison of small-strain shear modulus between in-situ and laboratory (Kokusho et al. 1994).

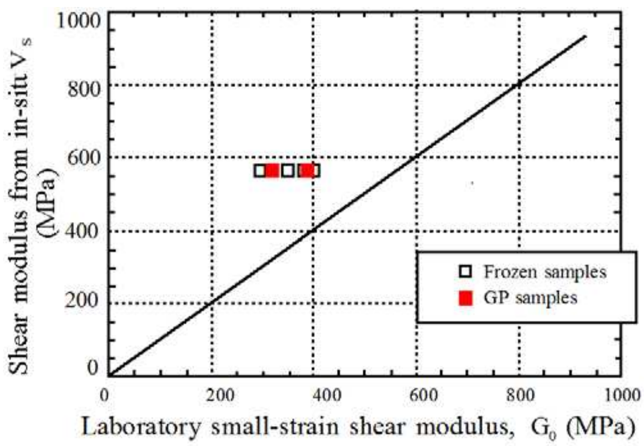


Figure 28. Comparison on small-strain shear modulus between in-situ and laboratory at Site K (GP-D data added to Kokusho et al. 1994).

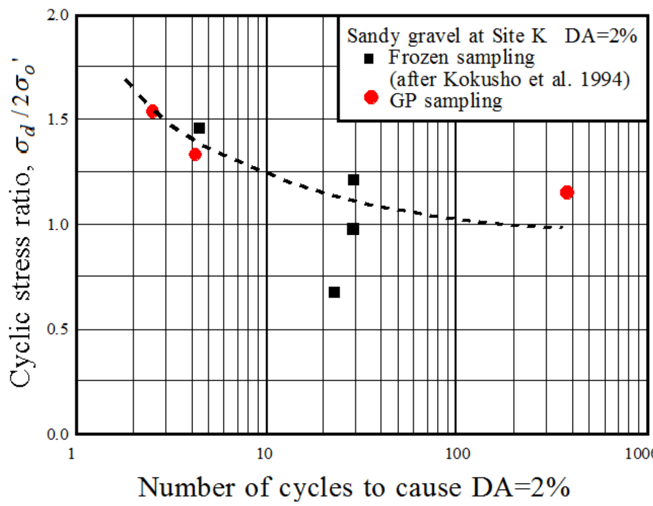


Figure 29. Cyclic stress ratio vs. number of cycles to cause DA=2 % for frozen and GP-D samples obtained at Site K.

From the results of shear modulus tests at small-strain, and undrained cyclic triaxial tests, it is justifiable to state that for the gravels at Site K, the GP-D sampling performed equally to that of the freezing method. It may not be appropriate to generalize the capability of the GP-D sampler with just one case record, but it seems reasonable to state that the sampler obtains high-quality samples of gravels.

3.3 *A case of sampling limestone and coral mixed gravel soils*

A limestone formation called Ryukyu Limestone is found in one of Japan's southernmost chains of islands, known internationally as the Ryukyu Arc. Okinawa Island is the largest in this chain and serves as its political and economic center. Ryukyu Limestone was formed in the Pleistocene Epoch, from the sedimentation of coral in the warm waters of the area, and widely distributed throughout the region. The formation is known for its wide variations in strengths and solidness, ranging from the solidified state by recrystallization, to cemented but unsolidified state. Cavities are also found in these limestone formations.

A cross-section of the Ryukyu Limestone formation, found in Okinawa is shown in Figure 30 (Arikawa & Sasaki 2008). The limestone formation is designated by Ls-1, Ls-2, and Ls-3, and the red zone in the center, with the SPT N-values showing large scatters. Conventional sampling produced very poor core recovery, as shown in Figure 31(a). Many of the structures built over the formation have had to be supported by piles, penetrating through the limestone to rest on the sounder mudstone formations found underneath.

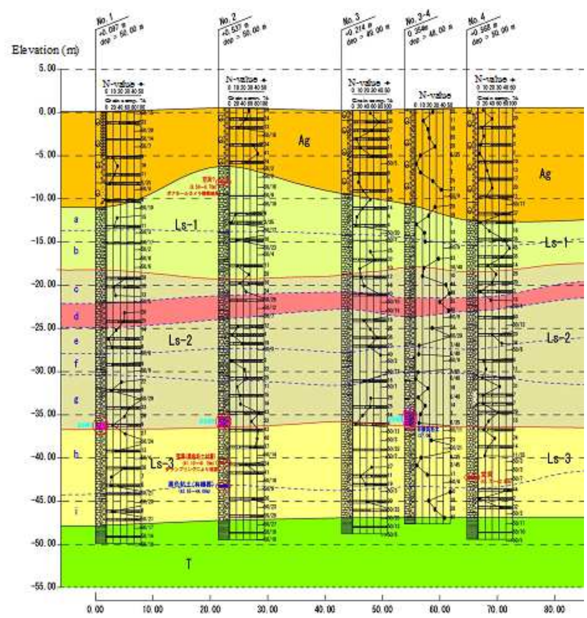


Figure 30. A cross-section of Ryukyu Limestone formation in Okinawa (Arikawa et al. 2008).

(a) Core samples obtained by conventional sampler (b) GP-D samples

Figure 31. Photos of Ryukyu Limestone core samples obtained by conventional sampling and GP-D sampler (Arikawa et al. 2008)

Since the thickness of Ryukyu Limestone often reaches 40 to 50 m on the shore, driving piles through the formation can become difficult and uneconomical. An attempt was made to obtain high-quality samples employing the GP-D sampler in order to more accurately ascertain the engineering properties of the limestone formation. Figure 31(b) shows two GP-D core samples obtained at depths of 23.0 m and 25.0 m. Contrary to the images of fractured cores and widely scattered N-values obtained through conventional sampling methods, the formation appeared to be more intact than previously thought.

Consolidated-drained triaxial compression tests were carried out on GP-D samples of the limestone obtained at depths of 26.7 m, 29.7 m, and 35.45 m as shown in Table 2 (Kokai et al. 2014). The SPT N-values, measured 1 m below the sampling depths, are also given. The samples at 26.7 m and 35.45 m came from relatively soft zones, but the laboratory tests showed reasonable soil strengths. The sampler core obtained at 29.7 m exhibited the strength of soft rock.

In the Ryukyu Islands, a more recent geological deposit called coral mixed gravelly soils, is found overlaying the Ryukyu Limestone. These soils are also difficult to sample with conventional samplers. Here, the GP-D sampler once again proved successful in obtaining high-quality samples. Figure 32 shows a photo of one such sample, and the CT scanning images taken of that sample. It is remarkable that the core scans reveal signs of past biological activity without disruption, indicating the superlative quality of the GP-D samples.

Table 2. Consolidated-drained traiaxial test results of Ryukyu Limestone (Kokai et al. 2014).

Sampled depth	GL-26.7m	GL-29.7m	GL-35.45m
Avg. N-value, 1m below	11	78	18
GP samples			
Moist density ρ_t (g/cm^3)	1.895	2.172	1.804
Fines content Fc (%)	37.3	31.8	22.2
Angle of int. fric. ϕ (°)	38.9	0	30.3
Cohesion c (kN/m^2)	0	1,270	0
Def. modulus E_{50}(MN/m^2)	37	459	22
Def. modulus $E_{(0.1\%)}$(MN/m^2)	101	862	82

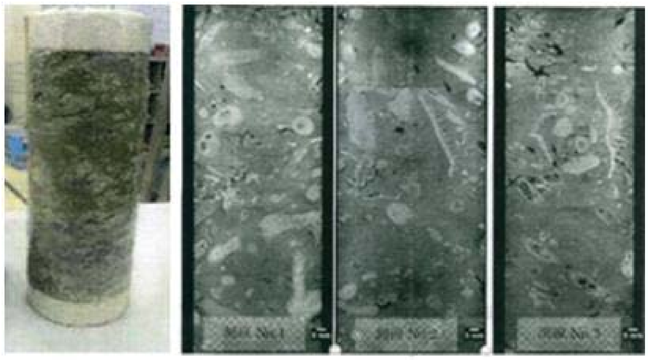


Figure 32. A GP-D sample of coral gravel mixed soil, and CT scanning images (Courtesy of the Port and Airport Research Institute, Japan).

Consolidated-drained triaxial tests carried out on the GP-D samples obtained from the coral mixed gravel formation at Miyako-Jima, one of the Ryukyu Islands, showed an angle of internal friction higher than those estimated by empirical equations using N-values (Ogawa et al. 2013). Similarly, the actual undrained cyclic strengths of the samples were stronger than the undrained cyclic strengths estimated using the SPT N-value based empirical equation. This equation is taken from the *Specification for Highway Bridges*, published by the Japan Road Association.

Upon reviewing the GP-D sampler data from the Ryukyu Limestone and coral mixed gravelly soil, it is evident that the GP-D sampler demonstrated its ability to successfully sample very brittle soils that conventional samplers had previously failed to do. These quality samples enabled engineers to observe and test cores that accurately represented the strength and deformation characteristics of the Ryukyu Limestone formations and coral mixed gravelly soil.

The GP-D sampler was the first sampler to succeed at obtaining intact samples of Ryukyu Limestone. This made thorough testing of the core samples in the laboratory feasible and ushered in a breakthrough in how limestone is analyzed

4 THE GP-TR SAMPLER

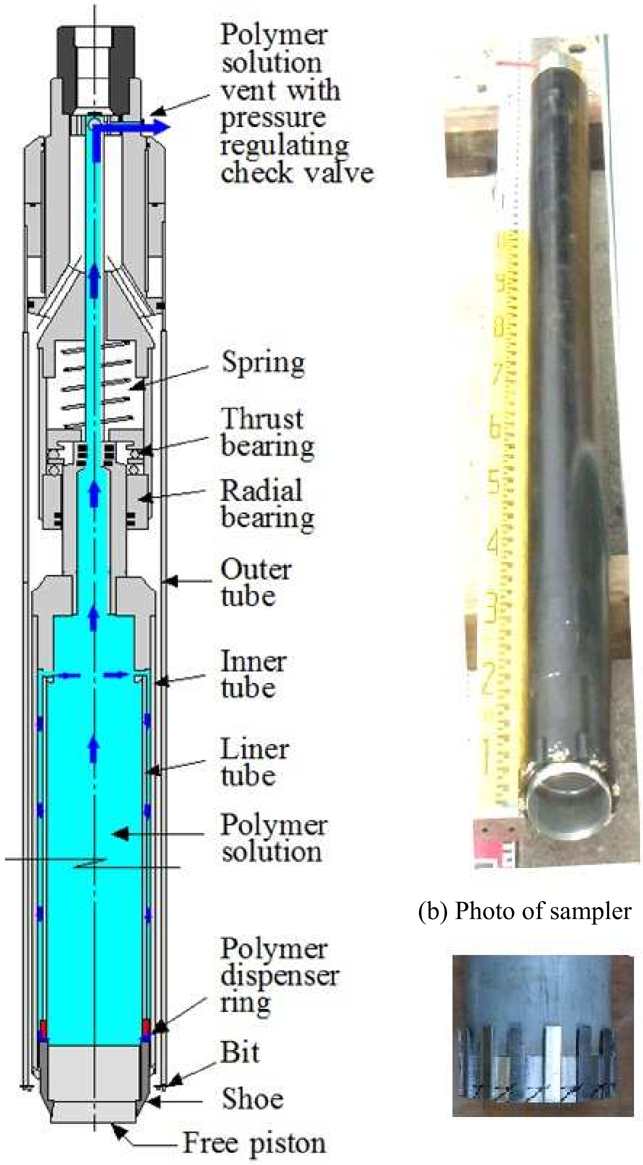
The GP-Tr sampler is designed for sampling medium to dense sandy soils. It can sample sand containing some gravel, but not gravelly soil. As with all GP samplers, the GP-Tr uses the polymer solution in a unique way: relying on it as a lubricant to reduce the friction between the sample and the sampler tube. In this section, the design of the sampler, its operating procedures, and three case records of site investigations using the sampler, are discussed.

4.1 *The design of GP-Tr sampler and its operations*

As shown in Figure 33(a), the GP-Tr sampler's construction is based upon a conventional rotary triple tube sampler, retaining the triple tube's basic features, including: self-adjusting shoe penetration; stationary liner and inner tubes; and an outer tube, tipped with a bit, that is employed to rotate and drill the soil above the shoe. Figure 33(b) shows a photo of the sampler. Unlike the GP-R and GP-D samplers, the GP-Tr utilizes ordinary drilling fluid to remove the cuttings and cool the bit.

Differentiating the GP-Tr design from common triple tube samplers, is its exclusive use of polymer solution to lubricate the core sample as it enters the liner tube. This is accomplished as a small volume of polymer solution is dispensed just above the shoe through a dispenser ring. The ring is attached to the bottom end of the PVC liner tube, as shown in Figure 33(c). The polymer flows through 45 degree cuts in the dispenser ring and comes into contact with the entering core, after it passes through the shoe, coating the sample surface with polymer solution. This significantly reduces the friction between the sample and the liner tube, which is one of the most serious causes of sample disturbance.

Another unique component of the GP-Tr is the free piston. The piston is designed with a ridge which catches on a lip inside of the shoe. This prevents the piston from falling out, and allows it to act as a stopper; storing the polymer solution inside the liner tube of the sampler. Once the sampling starts, the cored sample moves through the shoe, pushing the free piston up along the liner tube. In turn, the piston squeezes the polymer solution, forcing it to flow out of the liner tube chamber into an annular space between the liner and inner tubes. Once there, some of the polymer flows downward and is delivered to the dispenser ring to coat the sample.



(b) Photo of sampler

(a) Cross section

(c) Photo of polymer dispenser rinng

Figure 33. Schematic illustration and photo of GP-Tr sampler.

A very small percentage of the polymer solution which originally filled the liner tube is actually used for this coating. The excess is vented out through a check valve located at the top of the sampler. The check valve has two functions: first, it blocks the ordinary drilling fluid used from entering into the liner chamber, contaminating the polymer solution; second, it protects the core sample by preventing the polymer pressure from building up above a few kPa. A higher pressure would result in the polymer penetrating into the cored sample, which is a very undesirable condition. To help avert the possibility of this event, it is imperative to carry out the coring slowly, and avoid applying any abrupt thrust force to the sampler.

Figure 34 is a schematic illustration of the GP-Tr sampling process: first depicted is the positioning of the sampler at the floor of the borehole; next is the coring process nearing midpoint, with the sampler half way into the ground; finally, a drawing of the retraction of the sampler, with the sample core captured inside. Figure 35(a) shows a photo of the sampler with the piston and polymer solution in place, ready to be lowered into the borehole. As seen in Figure 35(a), the shoe is retaining the free piston prior to drilling.

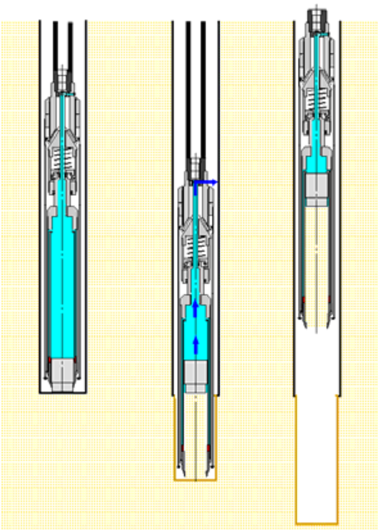


Figure 34. Schematic illustration of GP-Tr sampling.

(a) Photo of free piston (b) After sampling (c) Bit and shoe removed

Figure 35. Photos of GP-Tr sampler before and after sampling.

Figure 36. Photos of GP-Tr sample extruded out of the liner tube (above) and polymer solution wiped off (below).

The sampler is designed to obtain a sample length of up to 1 m. The shoe's tapering angle is set at 14 degrees in order to form the lip that serves to retain the free piston, preventing it from falling out. The inside diameter of the shoe is set between 80 mm and 83 mm to have an inside clearance ratio of 0.6 % to a maximum of 3.6 %. The area ratio ranges from 12 % to 21%. It is customary for a drilling operator to carry several sets of shoes for the best sampling results. The operator typically sizes the shoe, starting with the shoe having the least inside clearance and sizes up if necessary.

Figure 35(b) shows the sampler with a sample inside, while (c) shows the sample with the bit and shoe removed. Figure 36 shows the sample extruded out of the liner tube, still coated in polymer (above); and with the polymer removed (below). GP-Tr samples are usually kept upright in the liner tube overnight in order to facilitate the drainage of water. This ensures that the samples regain strength and stability before being sealed for shipment to the laboratory.

4.2 *A case of sampling at Zelazny Most, Poland, copper tailings disposal depository*

Jamiolkowski et al. (2015) report on comprehensive geotechnical site investigations, carried out over a period of two decades, at one of the world's largest copper tailings disposal reservoirs, located in Zelazny Most, Poland. In view of the difficulties associated with obtaining undisturbed samples of silt and silty sand at the tailings depository, the investigation relied primarily on in-situ tests including: S-CPTU; S-DMT; cross-hole tests; and block sampling. In 2013, a GP-Tr sampler was brought in and succeeded in obtaining quality samples.

Figure 37 shows the zone of gradation curves of the tailings disposal at location 7E-8E, close to where the GP-Tr samples were obtained. One of the gradation curves of the GP-Tr samples, taken at the site, is also shown. The specific GP-Tr sample used appears to be sandier than the surrounding area. Figure 38 shows the shear wave velocities determined by cross-hole tests at location 7E-8E, and the shear wave velocities measured in the laboratory using GP-Tr samples. The figure also shows the measurements normalized at 98 kN/m^2 in order to remove the effect of overburden pressures on the shear wave velocities. A good overall agreement seems to exist between the in-situ and laboratory measurements.

The normalized shear wave velocities were replotted to show the ratio of the velocities in the laboratory to in situ, against the normalized in-situ velocities, see Figure 39. This figure clearly demonstrates the relative difference between the two normalized velocities. All the data lie between normalized in-situ velocities of 200 and 300 m/s. However, the ratios of normalized shear velocities show a wide scat-

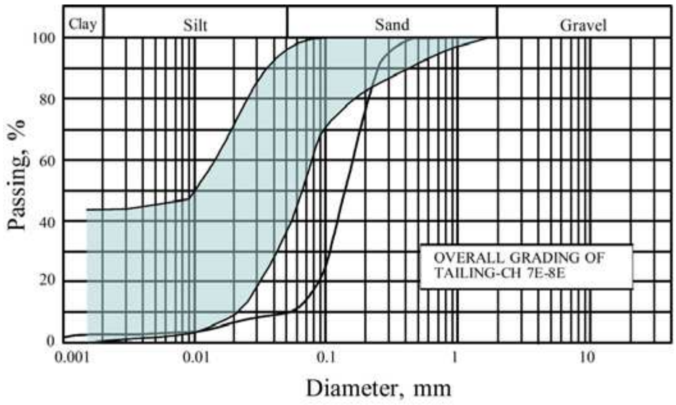


Figure 37. Gradation curves of tailings at 7E-8E and GP-Tr sample (Jamiolkowski et al. 2015).

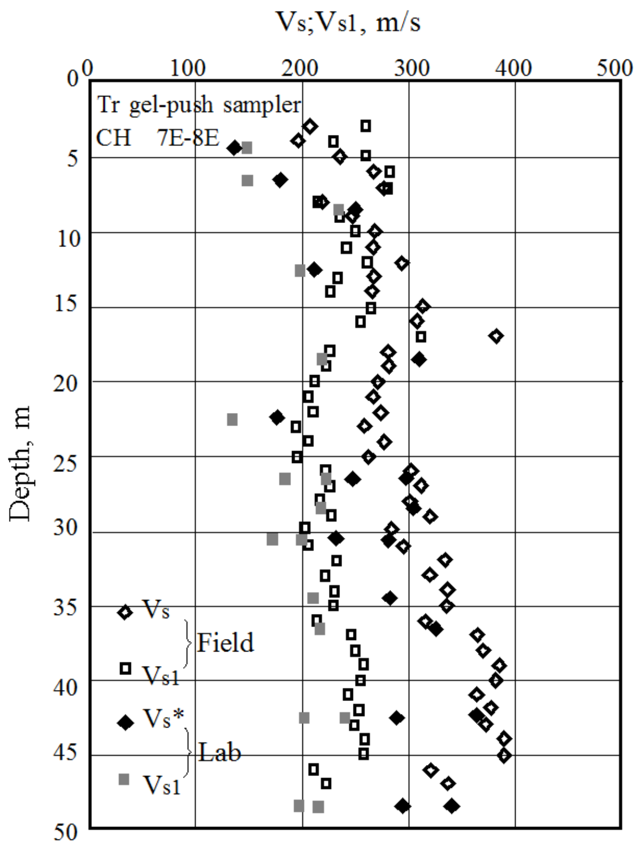


Figure 38. East dam-Comparison Vs1(F) vs. Vs1(L).(*) Bender element test. Geoteko (2014) (after Jamiolkowski et al. 2015).

ter, falling between 0.5 to 1.3, and indicating a possible divergence in the sample quality. In general, samples having shear wave velocity ratios close to unity are considered high-quality. It is however noticeable that many of the data points lie between 0.8 and 1.0, indicating these samples retained high-quality. It may be of value to compare the stress paths of static and cyclic loading tests using the samples having the ratios close to unity, with those having very large or small values to examine the possibility of sample disturbance. Since block sampling has been conducted on the site, it may also be

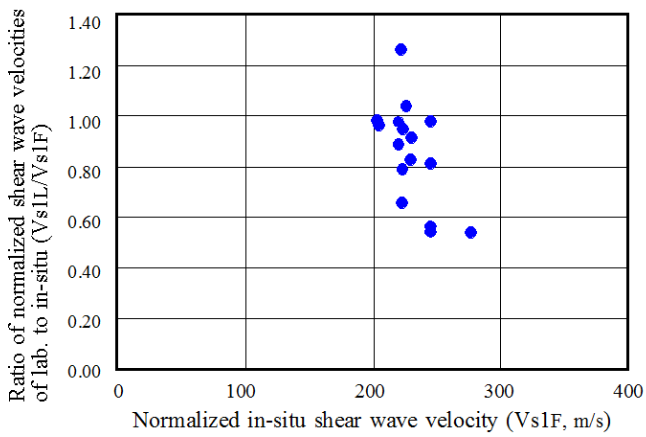


Figure 39. Ratio of normalized shear wave velocities of laboratory to in-situ vs. normalized in-situ shear wave velocity.

of interest to compare the strength and stress paths of the GP-Tr and block samples, as block sampling can preserve soil characteristics in situ (Mori et al. 1979).

4.3 *A case of sampling at Padma Bridge Project in Bangladesh*

Padma Bridge is located about 30 km southwest of Dhaka, crossing the Padma River in the district of Mawa on the left bank; and in the district on Janjira on the right bank. The bridge is under construction. When completed, it will become one of the longest bridges in Bangladesh, having a total span of 6.15 km.

The Padma River occasionally becomes turbulent, and is known to scour the riverbed to a depth in excess of 60 m. Thus, the piles supporting the bridge have to be primarily supported by the soil below the scour level. The soil formation at the site is predominately sand, with some gravel layers appearing. Layers of mica are also found. Seismicity of the area is moderate. However, for the stability analysis of the bridge structure, liquefaction susceptibility of the shallow sand formation was investigated.

A very comprehensive geotechnical investigation program was carried out as reported by De Silva et al. (2010): SPT; CTP; seismic survey; Dilatometer; pressuremeter tests; SB-IFT (self-boring in-situ shearing apparatus); and GP-Tr sampling. SB-IFT equipment and GP-Tr samplers were brought in from Japan and used at three locations, reaching to depths of about 100 m. To date, this is the deepest the GP-Tr samplers have been used.

Figure 40 shows: SPT N-values; sample recovery ratio; dry density; void ratio; the maximum and minimum void ratios at one of the boreholes. From the SPT N-values and the void ratios, the soil at Padma seems relatively dense. The gradation curves of the samples indicate the soil to be uniformly graded

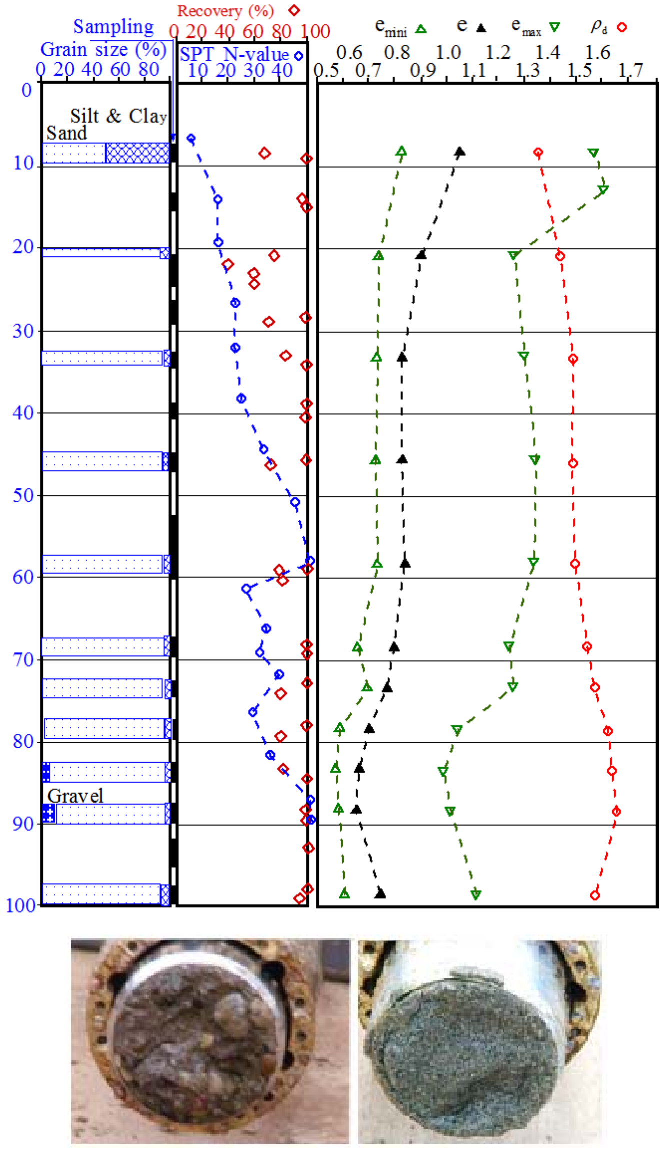


Figure 40. Soil profile at Padma site, and samples obtained at 58 m (left) and at 84 m (right).

clean sand, as shown in Figure 41. Since the seismic survey data is not yet available, the comparison of the laboratory determined shear wave velocities of the GP-Tr samples to those measured in situ, to assess sample quality, is not possible at this time.

However, with the results of undrained cyclic triaxial tests carried out on the samples, and using SPT N-values, an attempt was made to compare the Padma data with the data compiled by Matsuo (2004), on Japanese sandy soils obtained by the freezing method, as shown in Figure 42. The SPT N-values were normalized at 98 kN/m^2. The Padma data seems to agree overall with the general trend of the Japanese sandy soils. When the results of seismic and other in-situ tests, listed above, become available the quality of the GP-Tr samples obtained at Padma bridge project may be revisited.

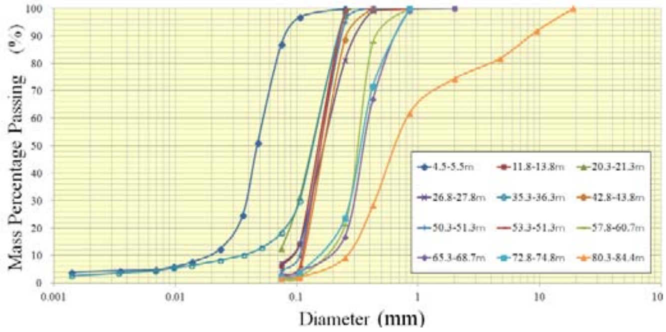


Figure 41. Gradation curves at Padma site.

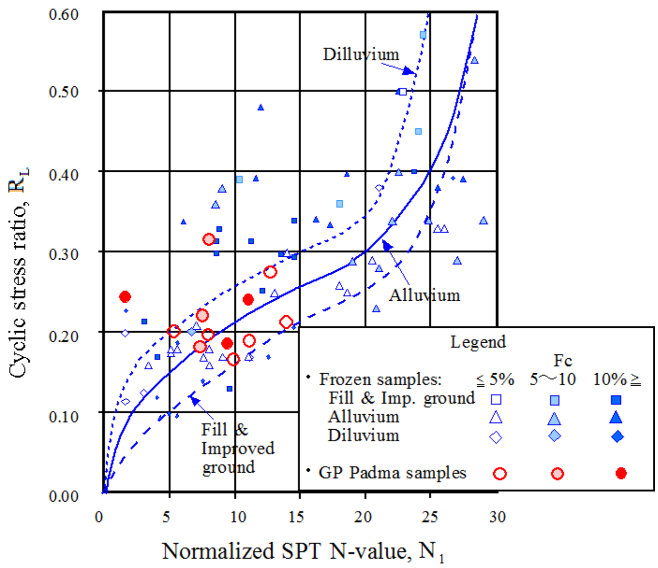


Figure 42. Cyclic stress ratio vs. normalized SPT value for frozen samples (Matsuo 2004), and GP samples obtained at Padma.

4.4 *A case of sampling of Jurong Formation*

The Jurong formation is a sedimentary rock formed from the late Triassic to the early Jurassic eras, and found in the western part of Singapore. It consists of conglomerate, sandstone, shale, mudstone, limestone, and dolomite. It has been severely folded, and the weathered section has become a residual soil.

This formation is known for its slaking characteristic. Slaking occurs when overburden pressures are lifted and the soil comes into contact with a fluid, including drilling fluid. In Singapore, the Mazier sampler, which is very similar in construction to the rotary triple tube sampler, is commonly used for sampling the formation. A sample taken from the formation utilizing this method exhibiting slaking is shown in Figure 43(a).

In an attempt to obtain higher quality samples of the Jurong formation, GP-Tr sampling was carried out at the same location and depth where the Mazier sample shown in Figure 43(a) was obtained (Yokoi et al. 2015). Figure 43(b) shows the GP-Tr sample. Both the Mazier and GP-Tr samples were obtained at a depth of 50.5 m. It is clear that the GP-Tr sample shows no trace of slaking. A total of seven samples, including the core sample shown in Figure 43(c), were obtained by the GP-Tr sampler along the depth of the borehole, none of which showed slaking. The gradation curves of two of the GP-Tr samples are shown in Figure 44.

Figure 45 depicts the undrained shear strengths of the GP-Tr and Mazier samples, which have been plotted against SPT N-values. Due to the limited amount of test data nothing conclusive can be stated, but it appears that the GP-Tr samples give somewhat higher strengths. When more data becomes available, it may prove the GP-Tr sampler to be a beneficial tool for assessing the engineering properties of the Jurong formation.

The GP-Tr's success in sampling the slaking-prone Jurong formation is attributable to its use of a thick polymer solution in the sampling process. The PHP polymer chain is negatively charged (anion), and attracted to the clay mineral's positively charged side (cation). Since clay mineral has a negatively charged side as well, the polymer chain is repelled at the same time. The combination of attraction and repulsion between the clay mineral and polymer strings forms a quasi-membrane, isolating the slaking-prone clay mineral and preventing it from being exposed to the drilling fluid. A polymer identical to the one used in GP polymer solutions is being marketed as an additive for drilling in slaking-prone formations. It has been demonstrated that using the polymer at high concentration makes it even more effective at preventing slaking.

(a) Mazier sample exhibiting slaking.

(b) GP-Tr sampled obtained at 50.5 m.

(c) GP-Tr sample obtained at 58.5 m.

Figure 43. Photos of Jurong formation samples obtained by Mazier and GP-Tr samplers (Yokoi et al. 2015).

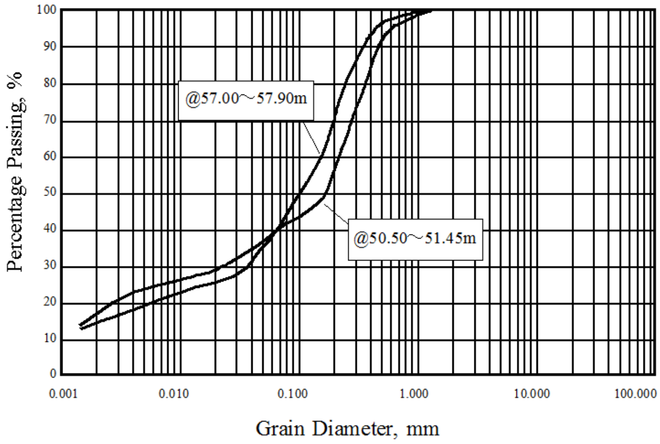


Figure 44. Gradation curves of two GP-Tr samples.

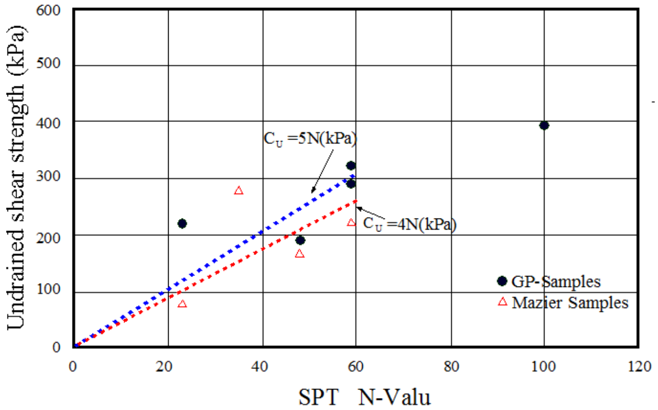


Figure 45. Relationship between undrained shear strengths and SPT N-Values of Jurong formation estimated from the samples obtained by GP-Tr and Mazier samplers.

5 THE GP-S SAMPLER

The GP-S sampler is designed to obtain high-quality samples of silt, silty sand, and loose sand. Unlike the other GP samplers, the GP-S does not use the rotational motion of a drill bit to obtain a sample. Instead, the sampler tube penetrates the ground statically. The design of the sampler, operating procedures, and actual case records, are discussed in this section.

5.1 *The design of GP-S sampler and its operations*

The GP-S sampler was developed as a joint project in 2006, between Kiso-Jiban Consultants and the Chinese Research Institute of Taiwan, led by Professor Lee. It is built around the Osterberg sampler design, with a fixed piston, and using hydraulic pressure to push the sampler tube into the ground.

The GP-S sampler has three pistons: the stationary piston, the sampling tube advancing piston, and the core-catcher activating piston. The stationary piston remains at the bottom of the borehole during the sampling. The sampling tube advancing piston pushes the shoe, the sampling tube, and the liner tube into the ground simultaneously.

As a major modification to the conventional Osterberg model, the GP-S sampler has a core catcher that is extended into position by a hydraulically activated piston. The core catcher acts to retain the cored sample, preventing it from falling out of the sample tube as it is retracted from the ground. The core catcher also dispenses a coating of thick polymer solution onto the surface of the cored sample, in a way similar to that of the dispenser ring in the GP-Tr sampler.

Figure 46 shows a cross-section of the sampler at three stages of sampling operation. Figure 46(a) shows the sampler at the bottom of the borehole. Figure 46(b) shows the shoe and sampler being pushed into the ground. Figure 46(c) shows the core catcher being activated and holding the core at the base of the shoe.

With the GP-R, GP-D and GP-Tr samplers, the cored sample entering into the liner tube, squeezes the polymer solution to flow up out of the barrel or liner tube, but with the GP-S, the sampling tube advancing piston squeezes the polymer solution down to flow out. Care must be exercised not to apply excessively high hydraulic pressure on the sampling tube advancing piston, which may cause the polymer pressure to rise too rapidly. A penetration rate of 1m/min is recommended. The polymer solution flows through the annular space between the sampling and liner tubes. Upon reaching the core catcher, the polymer solution seeps through the slight gaps between the diagonal fins of the core catcher to coat the sample, see Figure 47(a).

The sampling starts with the hydraulic pressure pushing the sampling tube advancing piston and forcing the entire sampling mechanism to move downward, see Figure 46(b). At this stage the polymer solution is being dispensed to coat the sample. Additionally, the polymer solution is being released to the outside of the sampler just above the shoe, to coat the exterior wall of the sampling tube, lubricating it to reduce the penetration resistance. As in the case of the GP-Tr sampler, the volume of polymer solution needed to accomplish these two tasks is limited and the bulk of the solution is vented out through a check valve at the top.

When the sampling tube is pushed down fully to

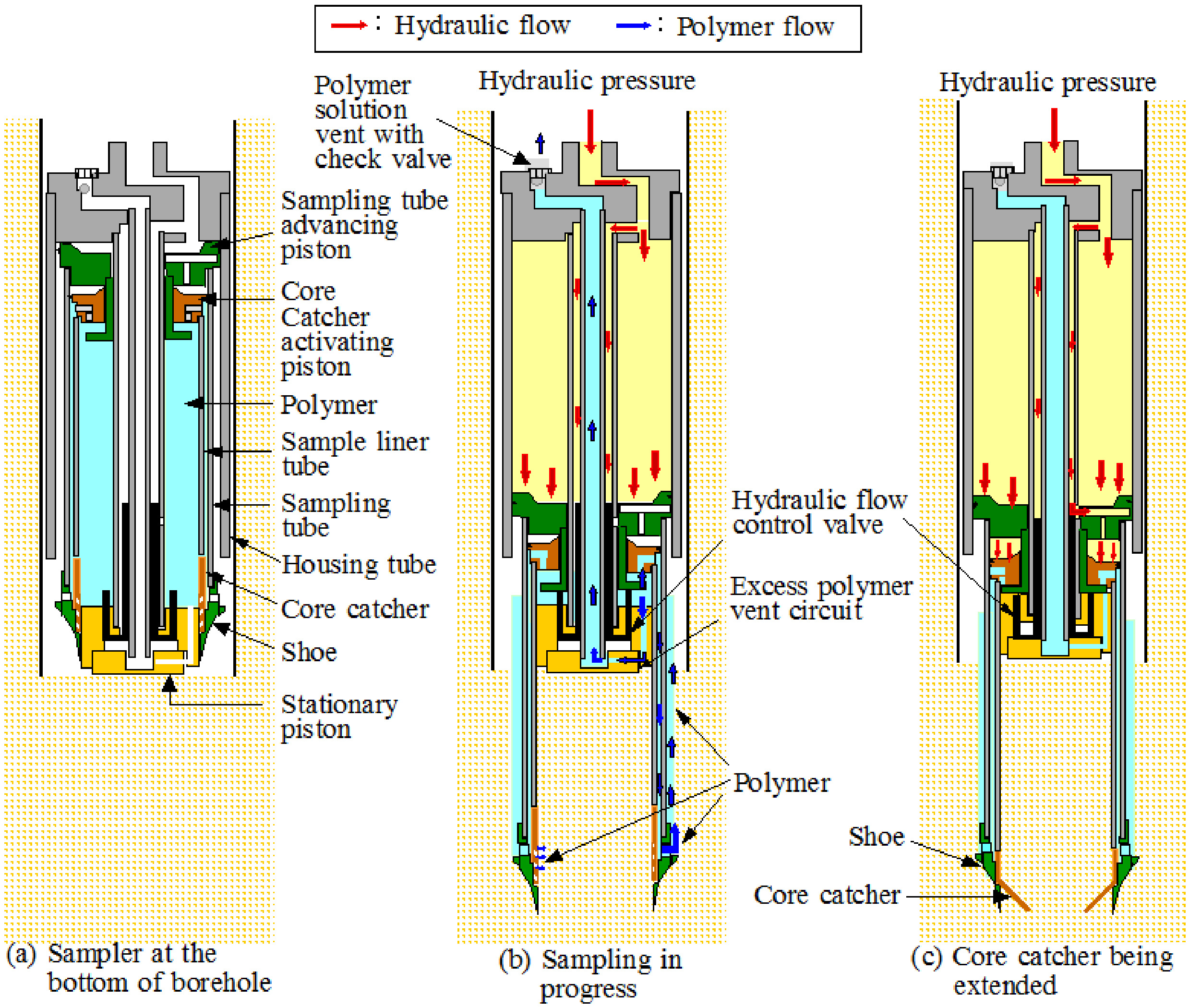


Figure 46. Schematic illustration of GP-S sampler in operation.

(a) Shoe and core catcher with piston removed.

(b) Activated core catcher with sample inside.

Figure 47. Photos of GP-S sampler.

a length of 1 m, it locks itself and shifts the position of the hydraulic flow control valve, shown in Figure 46(b). This diverts the hydraulic flow and triggers the core catcher activating piston. The piston forces the liner tube to move down, causing the core catcher to slide out of its resting position, extending its fins, as shown in Figures 46(c) and 47(b).

The fins ride over the inside wall of the shoe and extend out to constrict the cored sample at the shoe. The inside diameter of the shoe is made to be anywhere between 71 mm and 74 mm, while the inside clearance ratio is selected to be anywhere from 0.0 % to a maximum of 3.6 %. The shoe's tapering angle is set at 6.6 degrees, and the area ratio is set between 9 % to 18 %. Drilling operators usually carry several sets of shoes, and try to obtain quality samples using the shoe with the least inside clearance ratio.

Figure 48(a) shows a sand sample after having been removed from the liner tube with some polymer still visible. Figure 48(b) shows the sample with the polymer removed and the surface soil trimmed off to show the layering of the sample. As with the GP-Tr samples, GP-S samples are usually kept overnight upright in the liner tubes. This drains excess water from the sample, allowing the soil to reestablish stability before being sealed for shipment to the laboratory.

(a) Sample extruded out of liner tube.

(b) Sample surface trimmed off for examination.

Figure 48. Photos of GP-S sample.

5.2 *A case of site investigation at Muya coastal dyke, Japan*

The port of Muya is located in Tokushima Prefecture on the Island of Shikoku, as shown in Figure 49. The coastal area in western Japan expects to be subjected to an earthquake having a magnitude in excess of 8, with accompanying subsequent tsunami waves. An investigation has been carried out to study the seismic stability of soils at Muya port coastal dike.

In the course of the geotechnical investigation suspension type seismic survey, GP-S, thin walled tube, and triple tube samplings were carried out. Per the consent of the Komatsujima Port & Airport Construction Office, Shikoku Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, the following data and information is made possible.

Figure 50 shows the cross-section of the dike at Muya port. As the gradation curves shown in Figure 51 indicate, all the soil layers except the clay layer Ac2, fall in the zone of very likely to liquefy. GP-S samples were obtained at Layers B, Asc1, and Asc2. The fill material used behind the dike consists of coal cinders and some gravel, having SPT N-values between 5 and 10. A thin walled tube sampler was used for Layer Asc1, and a triple tube sampler for Layers B and Asc2. Figure 52 shows the photo of a GP-S sample obtained from Layer B containing coal cinders. It is evident the material is loosely packed.

In order to evaluate the sample quality, shear modulus determined in the laboratory using wave propagation method were compared with those determined from the in-situ seismic survey, as shown in Figure 53. The ordinate shows the ratio of shear modulus determined in the laboratory to the in-situ, and the abscissa shows the in-situ shear modulus. Most of the shear modulus ratios of the GP-S samples lie close to the axis of unity, indicating the samples were likely to have retained their high-quality.

The shear modulus ratios of the samples obtained

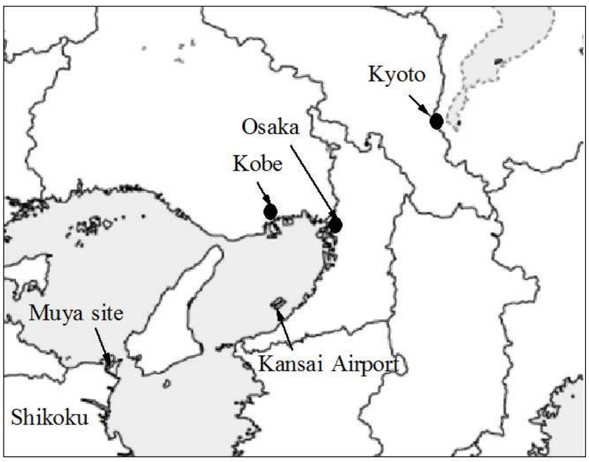


Figure 49. Location of Muya site.

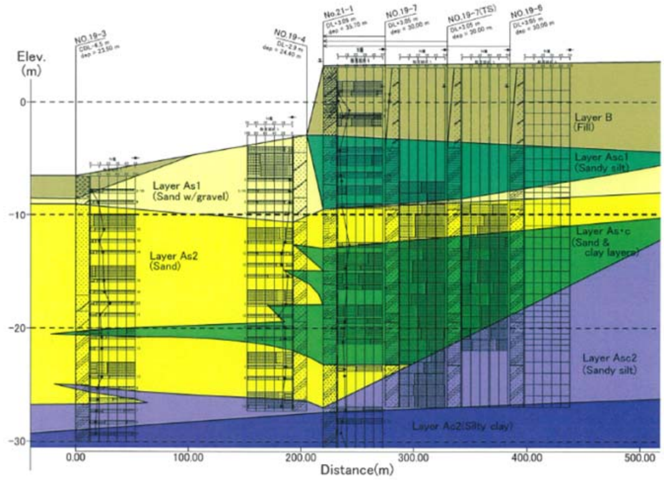


Figure 50. Cross-section of Muya Port coastal dyke.

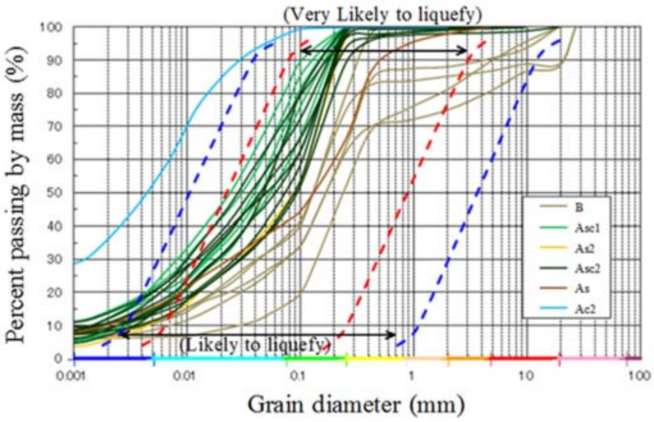


Figure 51. Gradation curves of soils at Muya Port.

Figure 52. Photo of Layer B sample.

by the thin walled tube and the triple tube samplers show a wide scatter, possibly indicating disturbance due to the sampling. At the Muya site, soil composition varies even within the same layer, and the samples obtained by the GP-S and thin walled tube or triple tube samplers for each layer may not necessarily have the same or similar soils. Consequently, the direct comparison of the GP-S samples with

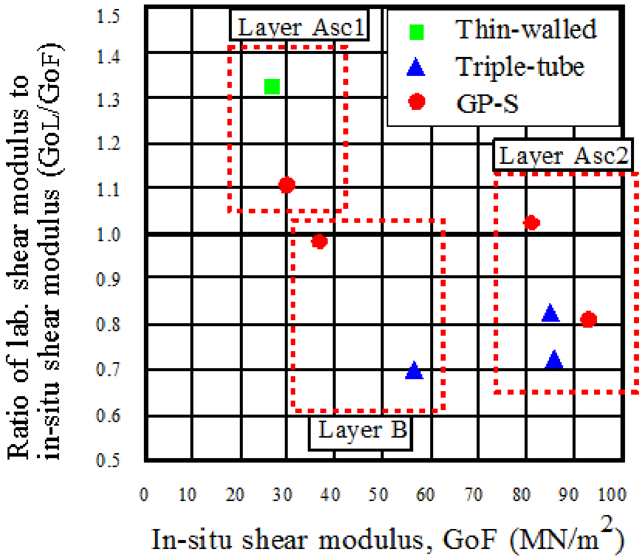


Figure 53. Ratio of shear modulus in the laboratory to in-situ vs. in-situ shear modulus (revisions made to Sunakawa et al. 2010).

samples obtained by other samplers, for each of the three layers, is not possible. However, the polymer coating system of the GP-S sampler appears to be effective in reducing friction between the cored sample and the sampler wall, obtaining high-quality samples regardless of the variation in soil compositions.

5.3 *Cases of New Zealand and Taiwan*

Outside Japan, the GP-S sampler has been used in New Zealand and Taiwan for sampling of silt and silty sands. Stringer et al. (2015a, b), Taylor et al. (2012), and others have reported the site investigation and liquefaction analyses carried out at Christchurch, subsequent to the 2010-2011 Canterbury Earthquake Sequence.

At Christchurch, extensive seismic surveys were carried out. One such set of data collected at Gainsborough Reserve site was used to compare with shear wave velocities measured in the laboratory using GP-S samples obtained at the same location, as shown in Figure 54. In-situ shear wave velocity was measured by the cross-hole method. The in-situ and laboratory shear wave velocities seem to agree very well, except for one GP-S data plotted at a shallow depth, where the sample was reported to have contained some organic fibers, causing the quality of sample to be suspect.

The shear wave velocity data was replotted, as shown in Figure 55, to compare the ratio of shear wave velocities of laboratory to in-situ, against the in-situ velocity. Since most of the data plots around the ratio of 1.0, the samples are considered high-quality.

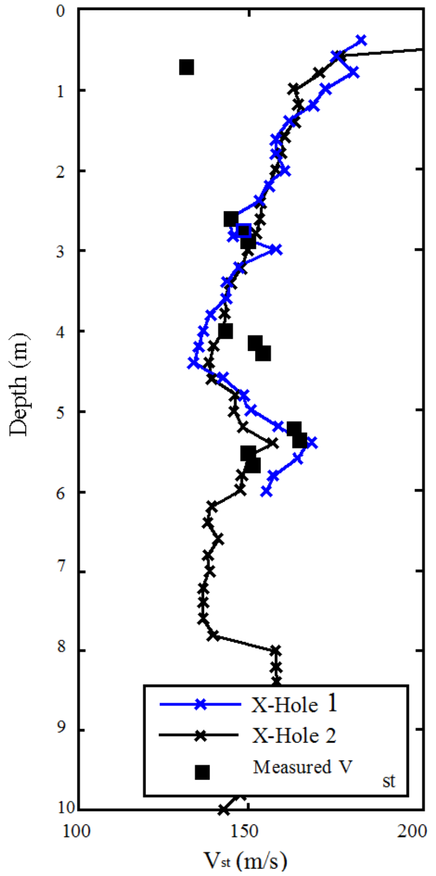


Figure 54. Comparison of shear wave velocity measured by the cross-hole at Gainsborough Reserve to the same determined using GP-S sample (Stringer et al. 2015b).

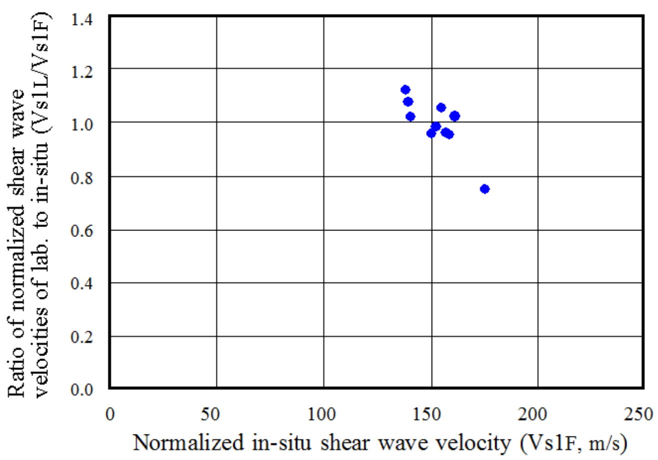


Figure 55. Ratio of normalized shear wave velocities of laboratory to in-situ vs. normalized in-situ velocity at Gainsborough Reserve.

In Taiwan, Lee et al. (2012), also carried out sampling of silty sand containing a high percentage of fines. They used the conventional tube, as well as GP-S samplers. Table 3 shows the sample recovery ratio and the fines content of the samples obtained. The recovery ratios for the GP-S sampler are consistently higher than those of the tube sampler. Although the recovery ratio does not necessarily assure the quality of samples, it may be considered a positive indication of quality.

Table 3. Comparison of sampling results between conventional tube sampler and Gel-Push sampler (Lee et al. 2012).

	Depth (m)	4.0-4.9	5.0-5.9	6.0-6.9	7.0-7.9	8.0-8.9	avg. of sample length (cm)
Tube sampler	No.	T2	T3	T4	T5	T6	54.6
	Sample length	64/80	50/80	55/80	58/80	46/80	
	Sampling ratio	80.0%	62.5%	68.5%	72.5%	57.5%	
	Fines content	24.0%	9.0%	-	20.3%	15.0%	
Gel Push sampler	No.	BT1	BT2	BT3	BT4	BT5	81.8
	Sample length	83/90	81/90	82/90	77/90	86/90	
	Sampling ratio	92.2%	90.0%	91.1%	85.5%	95.6%	
	Fines content	27.5%	24.3%	9.5%	14.5%	9.0%	

In Taiwan, the GP-S sampler performed satisfactorily. In New Zealand, sample quality evaluation using shear wave velocities measured in situ and in the laboratory proved favorable. In both Taiwan and New Zealand, local drilling foremen operated the samplers and obtained satisfactory results. However, due to the differences in drilling machines and sampling practices, it takes considerable time and care to make a mechanically complex sampler such as the GP-S operationally stable. The design of the sampler is under continuous review to ensure that it becomes simpler to operate.

6 CONCLUSIONS

GP samplers are relatively new entrants to geological site investigation. They have been in use primarily for sampling granular soils for the last fifteen years, during which time, the four GP sampler types have successfully obtained over 1000 core samples in Japan alone.

The use of a thick polymer gel or solution as a drilling fluid is a major departure from the concept of conventional drilling. Polymer solutions have been used as an additive to soil and rock coring, slurry wall construction, etc., but not at the high concentration levels used by the GP samplers. The polymer's non-Newtonian behavior, when used appropriately, delivers remarkable results.

The GP-R and GP-D samplers have proven their remarkable capabilities in obtaining high-quality samples of dense sand, gravel, and even sedimentary rock. These versatile samplers perform well beyond what would be expected from such seemingly simple construction. They employ a combination of thick polymer gel, an impregnated diamond bit, and an electric motor to obtain granular soils without freezing. With these samplers, the presence of fines has a nominal effect on sampling.

The sample quality of the GP-R and GP-D samples may be examined visually as these samples reveal a remarkable surface appearance, but for more qualitative evaluation, shear wave velocities or shear modulus are better indicators. In this paper, some of the in situ vs laboratory comparison cases are reported, with data indicating the overall good quality of the samples. An effort needs to be made to continue to collect these data to further confirm the samples' high-quality.

The GP-Tr and GP-S samplers are the latest additions to the GP family and have shown remarkable capability in sampling hard to obtain silt, silty sand, and sand. The polymer coating mechanism is innovative, but makes the design of the samplers complex and delicate to operate, which may need further refinement. However, the GP-Tr's success in sampling clean sand at a depth close to 100 m shows its high potential.

The GP-Tr and GP-S have been used outside Japan mostly with success, but some problems have been reported. The use of different types of drilling machines and sampling procedures seems to have contributed to these difficulties. Input from the experiences of overseas users will be most valuable for the next round of improvements on these two samplers.

The GP samplers have accomplished a great deal, obtaining samples that had previously been impossible or very difficult to collect with conventional methods. However, there is no end to the improvement of sampling technology, and the entire profession will benefit from the emergence of more innovative samplers.

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