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Water pressure test by wireline packer assembly to determine the in-situ permeability of rocks in deep geohydraulic test boreholes: practice method, equipment, and a case study

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Abstract. The data derived from geomechanical and hydrogeological investigations conducted in deep boreholes and in-situ tests play a critical role in ensuring underground engineering projects' successful design and implementation. Water pressure tests, frequently applied in hydrogeological, geotechnical, and mining projects, are integral for evaluating hydraulic properties such as the permeability of rocks. These properties, mainly influenced by discontinuities and the absorption characteristics of the rock mass, help assess rock tightness, grout efficiency, and geomechanical behaviour under various conditions like hydrofracturing and hydrojacking. Water pressure tests offer crucial insights into the in-situ permeability of rock. The Wireline Packer System provides a more efficient approach by allowing permeability tests to be conducted while the drill string remains in place, minimizing delays in operational time. Over the last 20 years, inflatable packer technology compatible with the wireline core drill string has evolved to meet the needs of deep geotechnical engineering applications. Therefore, deeper and more reliable water pressure tests can be easily incorporated into hydrogeological and geotechnical investigations. This study examined the properties of the specially manufactured inflatable tubing, composite cable, and other equipment, as well as the problems and solutions encountered during the application of these tests. The field water pressure tests were performed in 8 boreholes at 357–782 meter depths for the geotechnical investigation of a tunnel site. Suggestions are also made for techniques and equipment properties that should be applied in future successful water pressure tests in deep boreholes. The fact that the water takes values of the boreholes agree with those suggested in literature indicates that the tests were conducted successfully and the Lugeon values to be calculated are reliable.

***Keywords**: water pressure test; packer test; lugeon test; wireline packer; rock permeability; deep geotechnical test in borehole*

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INTRODUCTION

The water pressure test is widely used in geotechnical, hydrogeological, mining, and underground engineering applications. In the test, a pressure of kg/cm^2 is applied according to the properties of the rock, and the amount of water take (water absorption) is determined. By evaluating the data obtained from the test results, the amount of water absorbed is recorded on the test form, and the permeability class of the rock mass is determined. The test is performed by ISO (2012). The standard defines the procedures for conducting water pressure tests in boreholes drilled into rock formations. These tests help evaluate several key factors, such as the hydraulic properties of rock, which are predominantly influenced by discontinuities, rock mass absorption capacity, rock tightness, grout performance, and geomechanical responses like hydrofracturing and hydrojacking. The water pressure test is essential for determining the in-situ permeability of rock (Houlsby 1976; Pearson, Money 1977; Brassington, Walthall 1985; Swanson, Titone 2013; Zoorabadi 2023).

To conduct in-situ permeability tests, one or two inflatable packers seal off a section of the borehole, into which a measured volume of water is pumped under constant pressure (Giacomel, Rowe 1992). These inflatable packers isolate a section of the borehole, allowing for controlled water injection and enabling accurate measurement of the rock formation's permeability. There are standard configurations for inflatable packers during testing. The general approach for permeability testing is to use packers to isolate a borehole section, inject water at a consistent pressure, and measure the water flow rate to assess permeability. Before introducing more advanced systems, permeability testing was commonly performed using packers installed with drill rods or wireline methods. The drill rods technique was adapted into the wireline packer testing system patented by Sweeney (1982). This system enables the replacement of the inner tube in a wireline coring assembly through an inflatable packer system (Giacomel, Rowe 1992). After inflating the packers to isolate, a fundamental permeability test, often a water pressure test, can be performed by injecting water into the isolated zone (target zone) within the borehole through drill rods (Rowe, Ford 2017).

Gauging the in-situ permeability of rock formations by using packer tests is vital in hydrogeological, geotechnical, and mining projects. However, one of the main challenges faced in deep testing until recently was that packers were incompatible with wireline core drilling systems. Wireline core drilling utilized in mineral exploration for over 80 years has increasingly been applied in large underground projects. Its advantages, particularly in reducing time and costs at greater deep boreholes, are now widely recognized. To address previous limitations, Wimpey Laboratories Ltd. designed a packer testing system specifically for wireline drilling, utilizing equipment produced by Diamant Boart SA (Thomas 1982). Water pressure tests are performed using a wireline drill string in boreholes, whether stable or at risk of instability. Testing in deep boreholes is commonly conducted with wireline drill strings, as this method enables the drill rods to also serve as a conduit for the water supply. The packers and other equipment used in these tests differ in configuration depending on whether they are used in open boreholes or with wireline drill strings (Thomas 1982; Royle 2002; Adams, Roberts 2012).

It is planned to bring Sandras water resources to Muğla (south-western Turkiye) with engineering structures to meet the long-term drinking water needs of the province. In addition to the existing sources supplying water to the provincial centre, water well drilling studies were carried out for drinking water to be taken from Sandras - Çövenni water resources. Also, water pressure tests were carried out in deep boreholes drilled in the Muğla Drinking Water Transmission Tunnel Route (Fig. 1).

The study area consists of ophiolitic rocks (peridotite, pyroxenite, harzburgite, and serpentine) belonging to the northern part of the Lycian Peridotite (Marmaris Ophiolite Nappe) unit (Kaaden 1959; Engin 1969; Graciansky 1972; Juteau 1980). The Jurassic-Lower Cretaceous limestones are within the Lycian Nappes in the northwest and southeast of the study area. The ophiolite nappe is observed tectonically on the Jurassic-Lower Cretaceous limestones. In the northwest and southeast of the region, Tertiary sedimentary rocks consisting of conglomerates, sandstones, marls, and limestones are observed as angular unconformities (Fig. 1) (Özpınar 1987, 1995).

In this study, the properties of a specially manufactured inflating tubing, composite cable, and other equipment, and the problems and their solutions encountered during the practice of the tests were examined for the successfully carried water pressure tests in the eight boreholes at 357–782 meter intervals in depth for the geotechnical investigation of a tunnel route. Suggestions are also made for techniques and equipment properties that should be applied in future successful water pressure tests in deep boreholes.

WATER PRESSURE TEST BY WIRELINE PACKER ASSEMBLY

The most common methods for deploying packers include wireline, pipe, or hose. Among these, the wireline method, as depicted in Fig. 2, is the most widely used, particularly for retrieving core barrels on wireline coring rigs. This system offers several key advantages. First, the packer unit descends into a borehole via a wireline cable inside the drill rods, enabling it to move through the drill bit without the need to remove the rods. This results in significant time savings during test setup. Second, the borehole can be tested in sections as it is drilled, using a single packer, eliminating issues related to detecting leakage around a lower packer. Third, the packer is inflated, and the test is conducted using the existing water supply through the drill rods, eliminating the need for additional air or water lines, pumps, air bottles, or regulators to inflate the packer (Giacomel, Rowe1992). The Wireline Packer System is a highly efficient solution for conducting permeability tests during core drilling,

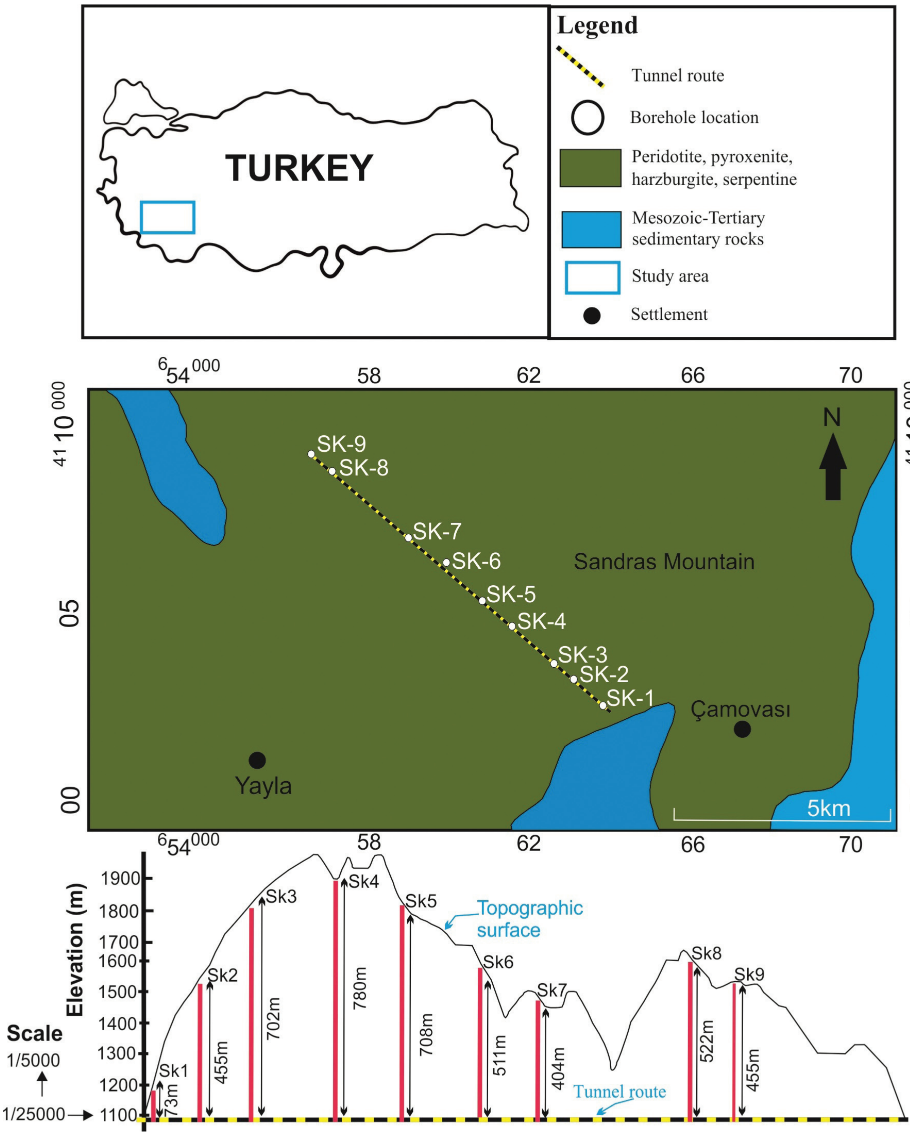

Fig. 1 The study area and its geology

as it keeps the drill string in place, reducing the time necessary for testing in open or unstable borehole formations. These wireline packers are designed with a bumper that rests within the throat of the drill bit, ensuring proper positioning for both the packers and the testing tools. Packers are compatible with all wireline core barrels (NQ, HQ, and PQ) produced.

The key characteristics of the system are shown in Fig. 2. Upon reaching the test section's bottom depth, the drill rods are retracted to a length equivalent to the test section. The outer sheath aids in positioning the packer within the borehole. Once the deflated section of the packer enters the water delivery pipe, the length can vary between 0.6 m and 1.7 m, depending on the specific ground conditions, allowing the ground to fill the annular space. After removing the core barrel, the packer is inflated, sealing the borehole annulus. The outer ends of the drill rods remain in place using the exact mechanism that secures the inner core barrel. Next, the packer unit is lowered to the bottom of the hole to test section two, with water flowing through a section and a valve at the top of the borehole. A deflated packer is then re-inflated, and packers close off the hole at the rods' bottom. At this point, water cannot flow into the borehole as the valve and the drill rod's end remain sealed. A rubber seal on the packer barrel's exterior interacts with the landing ring inside the outer core barrel, ensuring water does not leak beyond the drill bit (Giacomel, Rowe 1992).

Wireline packers are designed to enable open and drilled boreholes with the wireline drill string to be performed using drill rods to deliver the test water. To perform a water pressure test by wireline packers, the drill bit is pulled back a predetermined amount from the bottom of the borehole, and the packer system is lowered until the seating cone (bit seating sub) rests against the drill bit through the composite cable (containing rig wireline and inflating tubing). In this position, the system's lower packer (formation packer or open hole packer) is suspended just below the drill bit. In contrast, the upper packer (core barrel packer) remains in the core barrel just above the drill bit. Thus, when the two packers are inflated, the lower packer rests against the borehole wall, and the upper packer rests against the core barrel. In this case, the test zone is the section between the lower packer and the bottom of the borehole. The practice is similar in boreholes where the core barrel is not in the borehole (only casings or drill rods are present). In this case, the upper packer is inside the casings or drill rods, while the lower packer is suspended just below the casing shoe. A triple-packer system is required when performing straddle zone testing. In this case, the test zone in the borehole is the section between the middle and bottom packer (Fig. 3).

Packers are generally inflated using compressed gas, with nitrogen being the most common choice for safety reasons, mainly due to its non-flammability. A drawback of using it in deep testing conditions is that compressed gas poses the risk of surface-level bursts in inflation lines or fittings due to the elevated working pressures. Packers can also be inflated with water, hydraulic fluid, or antifreeze for deeper applications. One key advantage of water is that it is inert, meaning that even if inflation lines burst, they lack the same stored potential energy found in compressed gas lines. This makes water-inflated packers less risky. Additionally, the hydrostatic pressure of water in the inflation line will often match or exceed the surrounding formation's pressure, meaning less external pressure is needed for packer inflation. However, water and gas systems are susceptible to freezing in cold conditions. Antifreeze or hydraulic fluids can address this problem but may also present environmental risks. Brine solutions are another option, but they can lead to corrosion or negative impact testing by interacting with clay gouges in the rock formation, causing swelling and reducing permeability. These effects should be evaluated by analyzing the gouge material and conducting surface tests with the intended inflation fluid (Royle 2002).

Choosing the appropriate inflation fluid is influenced not just by the depth of the borehole but by the static pressure at the setting depth. For example, gas inflation might lead to over-expansion or bursting in softer formations like sand or clay, where significant pressure drops are undetected. Temperature is another factor: water is unsuitable for inflation if borehole temperatures exceed 100°C due to the risk of steam formation, and it is equally problematic in sub-zero conditions. The decision to use gas or liquid for inflation also depends on the permeability of the packer's rubber membrane, as gas may slowly permeate through the membrane over time, causing pressure losses. In such cases, using liquid inflation fluid might be more convenient to avoid the need for constant monitoring and replenishment. Ultimately, the choice between gas and liquid inflation fluid is often determined by availability and practicality, especially in remote areas where water may be the most accessible option for inflating packers under high pressure (Giacomel, Rowe 1992).

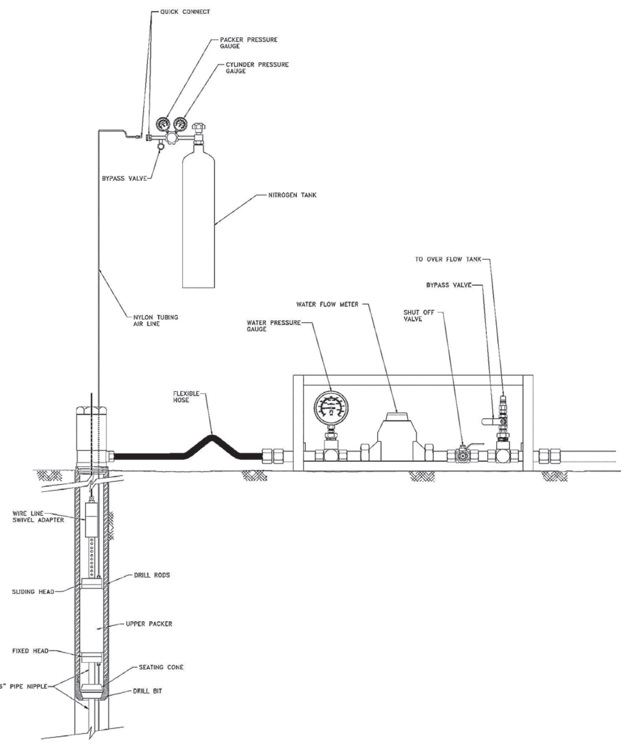

Fig. 2 A typical wireline packer test setup (from RST 2019)

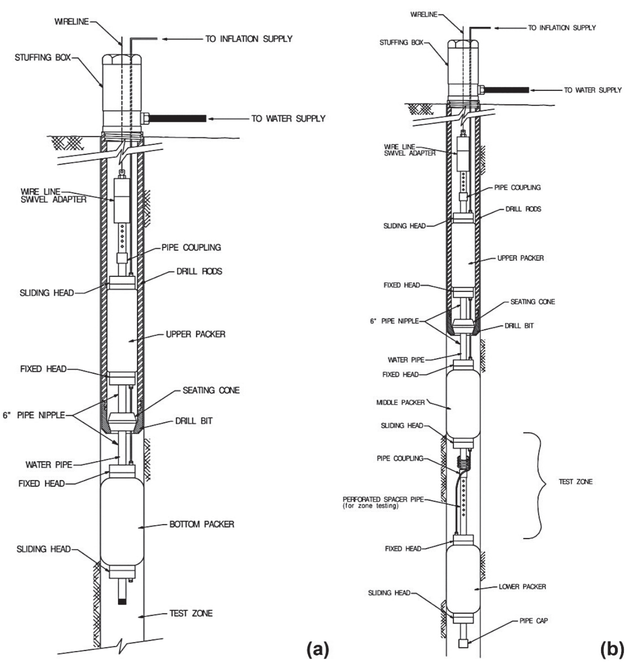

Fig. 3 Wireline double (a) and triple (b) packer setup (from RST 2019)

Hydraulic (water-inflated) packer systems were designed to overcome the drawbacks of gas-inflated packers. Packers were traditionally inflated using gas through a small-diameter hose extending from the surface for both drill rod systems and the more commonly used and convenient wireline systems. As testing depths increased, it became necessary to increase surface gas pressure proportionally to handle the rising static fluid levels, ensuring the proper inflation of packers and forming a seal against differential pressures during testing. While this method worked effectively at shallower depths, typically less than 300 meters. The introduction of water-inflated packers solved the high-pressure gas problems and expanded the range of water pressure tests that could be conducted. While water pressure tests continue to be performed as before, the absence of wireline or inflation tubing during testing allows for in-flow formation tests using pumping systems, such as airlift of submersible pumps placed inside the drill rods (Rowe, Ford 2017).

Table 1 and Fig. 4 illustrate the flow characteristics for various packer sizes and the approximate maximum permeability that can be measured based on a 3 meter long section tested under typical pressure in site investigations. In practice, HQ and PQ size packers are suitable for dealing with typical permeability ranges encountered during site investigations. However, the NQ packer, being slimmer in design, has a more restricted range of applications, and its expected permeability levels must be carefully assessed for use. The packers do not limit measurement at the lower end of the permeability range, which is determined by the accuracy of flow and pressure gauges used to measure minimal flow rates (Thomas 1982).

Over the last 20 years, inflatable packer technology compatible with the wireline core drill string has evolved to meet the needs of deep geotechnical engineering applications. Therefore, deeper and more reliable water pressure tests can be easily incorporated into geotechnical investigations.

DESIGN OF DEEP BOREHOLE AND DRILLING OPERATION IN THE STUDY AREA

Within the project's scope, nine boreholes were drilled deeper than 500 meters (Fig. 1). In all of the boreholes where ophiolitic units were used, rotary cutting drilling up to the test level and in test levels (in stages) penetrated diamond core drilling. Wireline equipment was used for core drilling. Because there is no need to pull the whole drill string out of the borehole to remove the core taken with wireline equipment, in this paper, the drilling operation in the borehole SK-4 and the application of the water pressure test will be examined.

In borehole SK-4, a 5 7/8" diameter tricone rock bit was first used to drill to a depth of 150 meters, and HW casing was set into the borehole (Fig. 5). Then, a 98 mm diameter PDC (polycrystalline diamond compact) bit was connected to the drill string, rotary cutting drilling to a depth of 600 meters, and NW casing was set. From 600 to 750 meters in depth, a 76 mm diameter PDC bit was used for rotary cutting drilling. During rotary cutting drilling, penetration problems were encountered occasionally due to instability in the ophiolitic units. To overcome these problems, the problematic levels were grouted with cement grout with a 1.75 g/cm^3 density. After waiting 24 hours (for the cement grout to freeze), a wireline drill string was inserted into the borehole, and coring operations were performed.

The wireline equipment was lowered into the borehole after cement grouting to prevent PDC bit

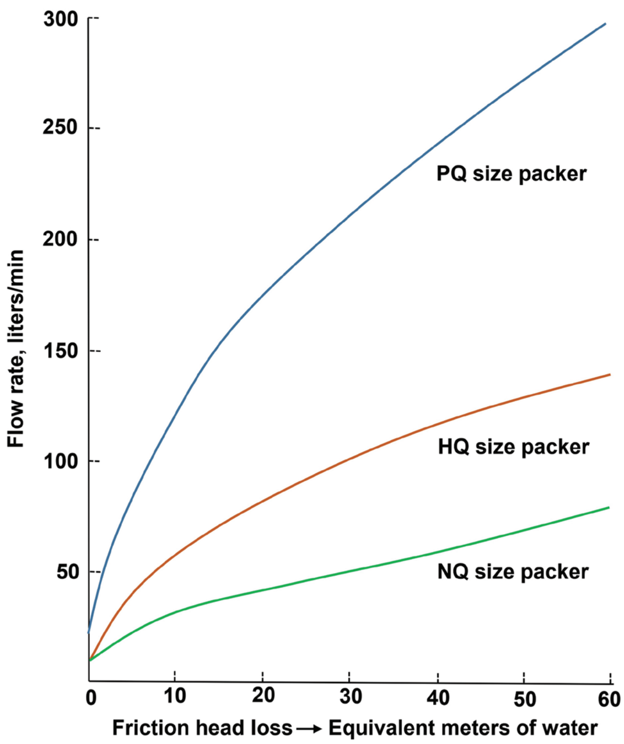

Fig. 4 Calibration curves of friction height loss for wireline packers (redrawn from Thomas 1982)

Table 1 Characteristics of wire-line packers (Thomas 1982)

Packer size	Borehole diameter (mm)	Internal diameter of water delivery pipe (m)	Maximum recommended water flow (litre/min)	Approximate maximum ground permeability measured	
				Lugeons	m/sec
NQ	757	12	30	80	1×10^{-5}
HQ	96.0	21	100	300	3.5×10^{-5}
PQ	122.6	25	300	800	1×10^{-4}

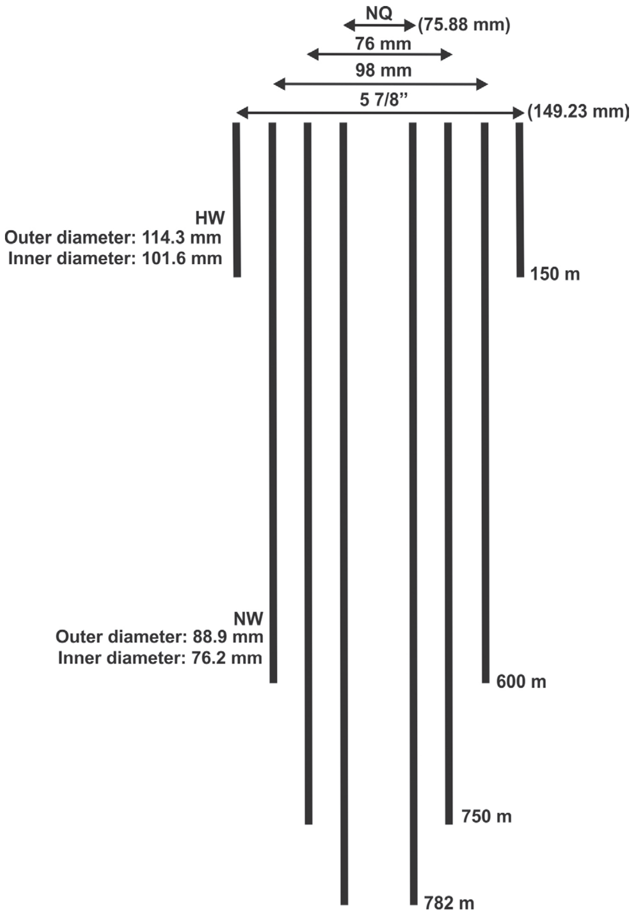

Fig. 5 The design of borehole SK-4

Fig. 6 Cement cores taken from the borehole with the wireline drilling equipment for controlling the grouting operation

damage during the drilling of cemented zones and to check whether the grouting operation was successful. Cement cores taken from the borehole with the wireline drilling equipment showed successful grouting (Fig. 6). As a result of this operation, formation stability was ensured, and the PDC bit could resume the rotary cutting drilling. At 750 meters in depth, the drill string was pulled back from the borehole, a three-meter NQ diameter core barrel was connected to the drill string, and the borehole was completed by coring to a depth of 782 meters (Fig. 7). CMC additive bentonite mud with 1.06–1.10 g/cm^3 density was used to drill the boreholes.

WATER PRESSURE TESTS BY WIRELINE PACKER ASSEMBLY IN THE STUDY AREA

In the deep boreholes drilled along the tunnel route, water pressure tests were conducted in 9 boreholes to determine the permeability (Table 2). Water loss was recorded at 5-minute intervals during the test by waiting 10 minutes at each test section (test length). The length of the test section to be applied in the test varies according to the physical and structural properties of the rock. In an impermeable and homogeneous rock, 5–10 m lengths can be applied, while in rocks with highly permeable and variable properties, the test length can be reduced to 1 m. Recovery pressures should be applied in highly permeable and variable water loss sections. Since it was understood during drilling that the ophiolitic units in the study area are weak and collapsible, water pressure tests by the wireline double packer assembly were applied in the boreholes (Figs 3 and 8). Water pressure tests were performed at pressures varying according to depth every 5 meters, starting from 10 m above the tunnel elevation in parallel with the penetration and up to 10 m below the tunnel elevation. In tests, recovery pressures can be applied in terms of time and cost. However, recovery pressures (first from top to bottom and then from bottom to top for each test section) were applied in the tests within the scope of the project since the application of recovery pressures is more accurate in terms of determining the properties of cracks and fractures in the sections of water injection and more precise test results are obtained. In the tests, a double packer system compatible with the wireline drill string was used (Figs 5 and 8). The core barrel packer (top string packer) was inflated inside the wireline drill string to prevent the pressurized water from returning. The formation packer (open hole packer) was inflated 5 meters above the test section. The tests were completed by measuring the water taken in each 5-meter section.

In the 782 m deep borehole, the necessary equipment was prepared for the test, and the packer was

Fig. 7 Cores were taken from 757–782 m depths, where water pressure tests were performed in borehole SK-4 (every section dimension of boxes is standardly 100 cm, and there are 5 sections in a core box)

Table 2 Water pressure tests conducted in the study area

Borehole no	X	Y	Borehole depth (m)	Test section (m)
SK-1	28.852°	37.050°	72	45–72
SK-2	28.842°	37.057°	589	565–589
SK-3	28.838°	37.059°	702	677–702
SK-4	28.826°	37.067°	782	757–782
SK-5	28.817°	37.073°	712	687–712
SK-6	28.807°	37.080°	542	517–542
SK-7	28.798°	37.086°	383	357–383
SK-8	28.775°	37.101°	505	480–505
SK-9	28.770°	37.103°	452	427–452

lowered to a depth of 782 m with a wireline. In the borehole with a groundwater level of 241 m, 20 bar pressure was applied through a pump to inflate the packer with water pressure. Since the packer did not inflate at this water pressure, 30 bar pressure was applied first, then 40 and 50 bar pressure was applied to inflate the packer. While checking whether the packer was held with the rig wireline, it was understood that the packer did not inflate or hold on to the borehole wall, and the packer was pulled back from the borehole. The drill string was moved 5 meters upwards, and a test was attempted at 777 meters in the borehole, which is 782 meters. However, the test could not be performed at this level either. Pulling the packer from the borehole was requested, but the packer could only be pulled back up to 500 meters. The drill string had to be removed from the borehole by breaking the rig wireline and the packer inflating tubing. When the rig wireline and inflating tubing were pulled back, it was observed that the originally circular inflating tubing became flat (flattened), and the different levels of the tubing stuck together. At a depth of 782 meters, it was concluded that the test was unsuccessful due to the pressure in the borehole and the fact that the borehole pressure could not be met despite the 50 bar pressure applied. The packer, stuck in the drill string, could be removed from the borehole by cutting the drill rods out of the borehole after the drill string was removed entirely. When the drill string was pulled back out of the borehole, it was observed that the packer was trapped (along with some hose) in the NQ rods at a depth of 350 meters.

Although the packer could be easily pulled back to a depth of 500 meters, it could not be taken from into the drill string. When the rig wireline and the hose connected with tape and plastic clamps started to be pulled back to take the packer from the borehole, it was observed that the hoses swelled and burst at the joints and weak parts of the hoses. It was also observed that although taped and clamped, it was stripped from the rig wireline and piled up in certain parts. The rig wireline and hose could be pulled back out of the borehole by breaking off due to the hanging process. This case concluded that in deep borehole tests, a combined (composite) cable design should be used to wrap the packer inflating tubing and rig wireline together (Fig. 9).

Due to the presence of 541 meters of water column (drill mud) in the borehole, it was concluded that an additional pressure of + 20 bar (60 + 20 = 80 bar) was required to inflate the packer with a pressure of 55 or 60 bar. Therefore, a special hose resistant to a minimum of 90–100 bar pressure was required for the application. It was also decided to inflate the packer in the borehole with air instead of water. A 1000-meter-long special steel wire hose resistant to 120 bar pressure was manufactured. A new drum was also installed on the drilling rig to wind this special steel wire hose, lower it, and pull it back to the borehole (Fig. 10). With this hose and drum system, deep tests could be performed without any problems by reducing the inner diameter of this 120 bar pressure-resistant hose (to reduce the pressure on the total internal area of the hose). The fact that the water take values of the boreholes (Table 3) are in agreement with the values suggested by Thomas (1982) (see Fig. 4 and Table 1) indicates that the experiment was conducted successfully and the Lugeon values to be calculated are reliable.

CONCLUSION

The water pressure test is widely used in geotechnical, hydrogeological, mining, and underground engineering applications. Over the last 20 years, inflat-

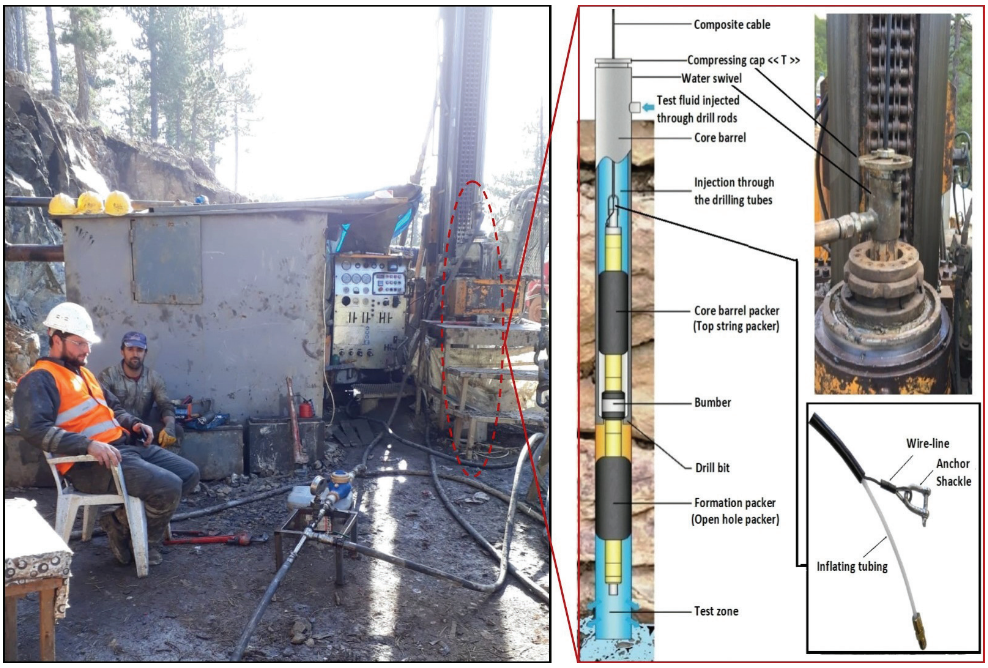

Fig. 8 Water pressure testing by wireline packer system in the study area

Table 3 Results of pressure gauge and flowmeter readings obtained during the test (borehole SK-4). Groundwater level in the borehole: 241 meters

Pressure step	(pressure, kg/cm^2)	2	4	6	8	10	8	6	4	2
Test section, m	Test duration (min)	Water takes (litre)								
757–762	1.5	28	30	32	35	37	39	37	34	30
	2.5	29	29	33	34	40	38	35	32	31
762–767	1.5	36	40	47	55	60	60	50	44	40
	2.5	35	42	50	57	62	61	49	43	41
767–772	1.5	52	56	57	68	70	62	49	47	45
	2.5	50	51	60	67	71	61	52	46	45
772–777	1.5	41	57	50	52	54	56	49	45	35
	2.5	40	55	51	53	55	56	50	44	40
777–782	2.5	41	61	65	71	75	72	66	62	42

able packer technology compatible with a wireline core drill string (all wireline NQ, HQ, and PQ core barrels) has evolved to meet the needs of deep geotechnical engineering applications. Therefore, deeper and more reliable water pressure tests can be easily incorporated into ground investigations. This study has presented the practice method, equipment, and a case study for water pressure tests by the wireline packer assembly to determine the in-situ permeability of rocks in deep geohydraulic test boreholes. Suggestions are also made for techniques and equipment properties that should be applied in future successful water pressure tests in deep boreholes. In deep boreholes, the pressure that can be applied to inflate the packer is related to the borehole conditions (groundwater level, etc.). For this reason, it is necessary to use steel wire inflating tubing resistant to high pressures for the application and to have an additional drum on the drilling rig for winding these inflating tubing lowered and pulled back into and out of the borehole. It is also more convenient to inflate the packer in the borehole with air instead of water. It is necessary to use a combined design where the packer inflating tubing and rig wireline are wound together. The fact that the water take values of the boreholes are in agreement with the values suggested in literature indicates that the experiment was conducted successfully and the Lugeon values to be calculated are reliable. Deep water pressure tests can be performed without problems if these conditions are met. The study is also thought to fill an essential gap in the literature on the subject which has a pretty limited number of studies in the literature.

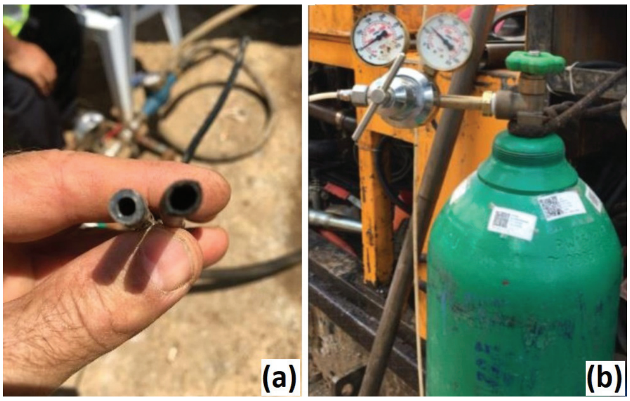

Fig. 9 Specially manufactured 120 bar pressure-resistant inflating tubing for the packer (a) and 150 bar pressure oxygen cylinder (b)

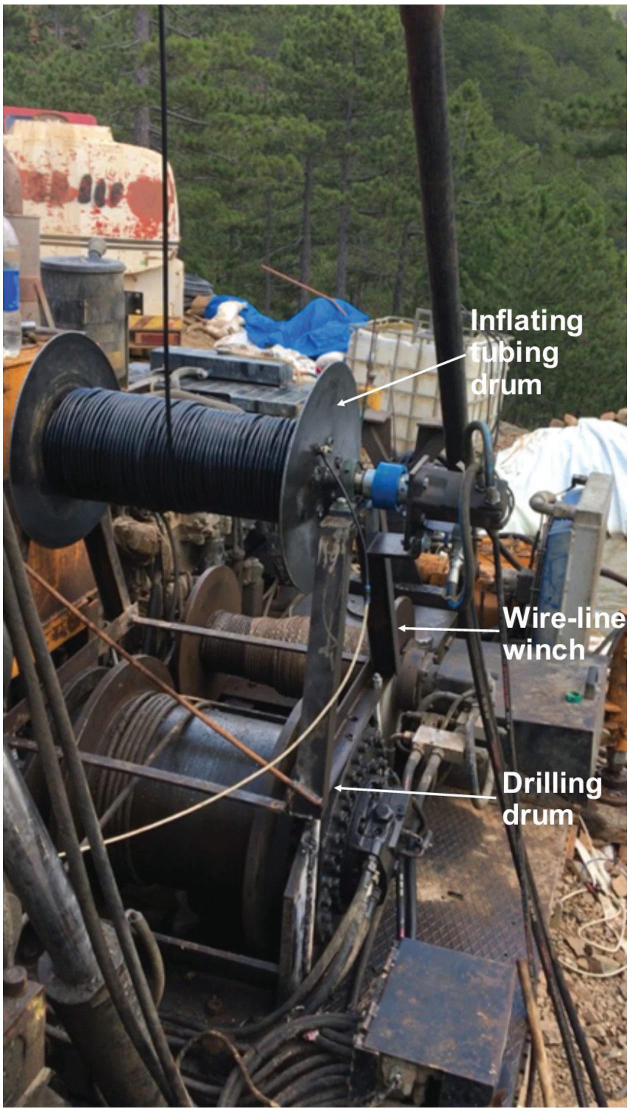

Fig. 10 Drum mounted on the drilling rig for winding inflating tubing and lowered into and pulled back out of the borehole

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