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V.P. Franchuk, Dr. Sci. (Tech.), Prof.,
T.V. Shepel

State Higher Educational Institution "National Mining University", Dnipropetrovsk, Ukraine, e-mail: franchuk@nmu.org.ua; sarat.dp@mail.ru

DEEP-SEA DREDGING EXPERIMENTAL RESEARCH IN THE BLACK SEA

В.П. Франчук, д-р техн. наук, проф.,
Т.В. Шепель

Державний вищий навчальний заклад „Національний гірничий університет", м.Дніпропетровськ, Україна,
e-mail: franchuk@nmu.org.ua; sarat.dp@mail.ru

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ПРОЦЕСУ ГЛИБОКОВОДНОГО ДРАГУВАННЯ В ЧОРНОМУ МОРІ

Purpose. Investigation of deep-sea dredging process based on the results of experiments that were carried out in the 73th voyage of Research Vessel "Professor Vodyanitskiy" during marine expedition in the Black Sea on 7–17 of June 2013.

Methodology. It includes experimental methods with tensometric and accelerometric tools, which were designed in the National Mining University. The tools were installed on the cable-bucket equipment used at the vessel "Professor Vodyanitskiy" for seabed sediment sampling. The experiments were conducted while digging organic-mineral sediments at the depth of 1885 m.

Findings. The results obtained give the diagrams, which allow to trace kinematics and dynamics of the scrapper dredge while digging seabed sediments. It has been established that there exist adverse operating modes of the mining equipment at which the dredge lowered to the bottom is characterized by unstable space position. The force of digging of organic-mineral sediments with the dredge 0.33 m^3 capacity also was determined. On the basis of the natural experiment, the principle about small influence of hydrostatic pressure on digging force at the development of water-saturated porous medium was confirmed.

Originality. The forces defined during natural experiment which influence at the bucket working tool allow verifying principles of the water-saturated ground cutting theory.

Practical value. The results can be used to justify the parameters of bucket-type working tools of deep-sea mining machines. Avoiding of detected adverse operating modes of the cable-bucket equipment of the vessel "Professor Vodyanitskiy" will reduce the probability of accidents during deep-sea dredging operations.

Keywords: *dredging, scrapper dredge, organic-mineral sediments, deep-sea mining*

Statement of the problem. The main part of the world mineral resources that have strategic importance are concentrated on marine bottom. From the latter half of the last century up to nowadays mankind has been trying to develop deep-sea solid minerals. Such a long term of solving this problem is caused by complexity and originality of the specified task.

Mineral resources of the Black Sea have a great economical importance for Ukraine. Besides oil, gas, polymetallic nodules, gas-hydrates and sulfides deposits, considerable reserves of organic-mineral sediments were found in the abyssal sea. After studies in Ukraine and Bulgaria, it has been found that the sediments may be of some economical interest for many countries of the Black Sea region. But to develop organic-mineral sediments mining, it is necessary to carry out some theoretical and experimental investigation aimed at the research and designing of mining and processing equipment.

Determination of the unsolved problem. Specific operating conditions of deep-sea mining equipment require development of the new approaches to defining loads on excavating part of an underwater earthmoving machine. Most of design methods associated with work tools load analysis are based on experimental investigations that were realized in a laboratory setting. It is concerned with great difficulties and costs of the field experiments as well as possible damage to the environment. The existing methods are grounded on a lot of theoretical assumption that can lead to significant errors.

The experience of organizations, which used to develop deep-sea mining sphere, is usually out of reach today. Any archive materials of the national research organizations in many cases were lost after the breakup of the USSR. However, foreign firms prefer to keep the results of their own investigation confidential for some economical, political and strategic reasons. So the new data about deep-sea earthmoving machines in the natural conditions operation may be useful for many researchers, who work on determining underwater machines working body parameters.

The purpose of this article is to provide the results of deep-sea dredging process experimental investigation taken during 73th voyage of research vessel "Professor Vodyanitsky" in the Black Sea (7–17th of June 2013) and to analyse the data obtained.

The main materials treatment. During marine expeditions to collect seabed sediment samples single-line dredge equipment was used at the RV "Professor Vodyanitsky" (fig. 1). The equipment includes a scraper dredge, a cable, a U-shaped frame on the vessel afterdeck and a multilayer winding winch. The cable from the winch crosses through the sheave wheel fixed on a U-frame and is connected to the scrapper dredge. The underwater equipment is dipped to off-vessel zone by U-frame inclining.

The experiment was carried out during sediments sampling with scrapper dredge 0.33 m^3 capacity (0.55x0.55x1.10 m) at polygon "Sapropel" (north-west part of the Black Sea) at 1885m depth.

Fig. 1. RV "Professor Vodyanitskij" technological equipment

The primary objective of the experiment was to study dredge kinematic and dynamic parameters during bottom sediments sampling. The accelerometric and tensometric equipment created in the National Mining University was used for the test. This equipment was fixed on the dredge. Electronic part included three-axis gyroscope, accelerometer, microcontroller, amplifier, millivoltmeter and other operational units. To protect electronics against mechanical damage and big hydraulic pressure, a special pressurized container was made (fig. 2).

Fig. 2. Pressurized container made in the NMU

Designed and produced in the NMU, the tension sensor (fig. 3) consists of the spring element and two strain gauges that are glued on opposite sides of the spring. A cable is fixed nonlinearly on the spring in three points. Spring deformation occurs under the cable tension. Both strain gauges are connected with direct and variable resistors into a bridge circuit. Moreover, strain gauges are hooked up in the related branches of the bridge. It allows compensating temperature and environmental pressure variations of the resistance.

Fig. 3. The tension sensor made in the NMU

Voltage variation in strain gauge bridge circuit was fixed by millivoltmeter. The signal from strain gauges to millivoltmeter, which is located in the pressurized container, was relayed through an electrical cable. Electronics power supply is provided by a 9 volt battery. The measurement record was stored on a compact flash drive with 10 Hz frequency.

The calibration test of the designed equipment was conducted in two phases. During the first one, it was necessary to find hydraulic pressure influence on the indicated value of strain-gauge instrumentation. For that purpose, pressurized container with electronics and tension sensor were put in the water hydrostat (fig. 4, *a*). Pressure in the hydrostat was increased with a high-pressure piston-type pump from 1 until 250 bars with the step of loading 10 bars and 5 min exposure at each step. After tests, it was found that pressure variation has no influence on the indicated value of strain-gauge instrumentation (in the tested pressure range).

The purpose of the second phase was graduation of the strain-gauge instrumentation parameters in accordance with the cable force. Cable stretching was carried out with 5-ton press (fig. 4, *b*). Tensile cable load varied from 0 to 7000 N with the step of loading 1000 N. After series of tests, loading-voltage dependence was obtained which allows to interpret strain-gauge instrument readings. With regard to the resulting function, regression equation with a coefficient of determination R^2 = 0,997 was derived. Maximum measurement error using the developed strain gauge measuring equipment is 150 N.

a *b*

Fig. 4. Test and calibration electrical equipment at the hydrostat (a) and the mechanical press (b)

For tests in the Black Sea, the pressurized container was fastened on the back wall inside the scraper dredge by bolting. The tension sensor was fixed on the rope sling by wire rope clamps. The layout scheme of the measuring equipment with the gyroscope and accelerometer coordinate axes is shown in fig. 5.

After electronics had been switched on, during the whole dredging cycle the following parameters were recorded in the log: the vessel speed, the ship's sonar indication, the cable lowering speed, duty cycle of the winch. The entries allowed to conduct further analysis of the obtained data in order to compare electronic equipment measurements with dredging process operations.

After sampling, the lifted dredge was loaded 50–60% full with coccolith sediments. The digging depth was at a range of 0.2–0.3 m by the visual estimation of excavated bottom ground. Hauling cable near the swivel was tangled, resulting in dredge inclination approximately 8–10° from the vertical.

After removing the flash drive from the pressurized container, the obtained data were transferred to a personal computer for processing in Mathcad software package. Oscillograms of cable force, graphs of dredge acceleration and inclination during the dredging cycle (fig. 6) were designed pursuant to the data processing results.

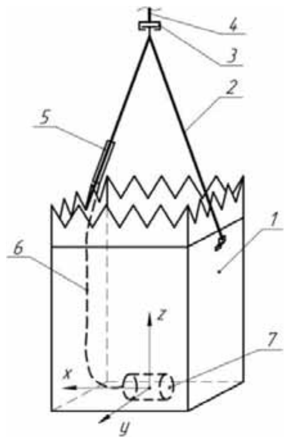

Fig. 5. Location scheme of measurement equipment on the dredge: 1 – ladle body; 2 – rope sling; 3 – swivel; 4 – hauling cable; 5 – tension sensor; 6 – electrical cable; 7 – pressurized container with electronics

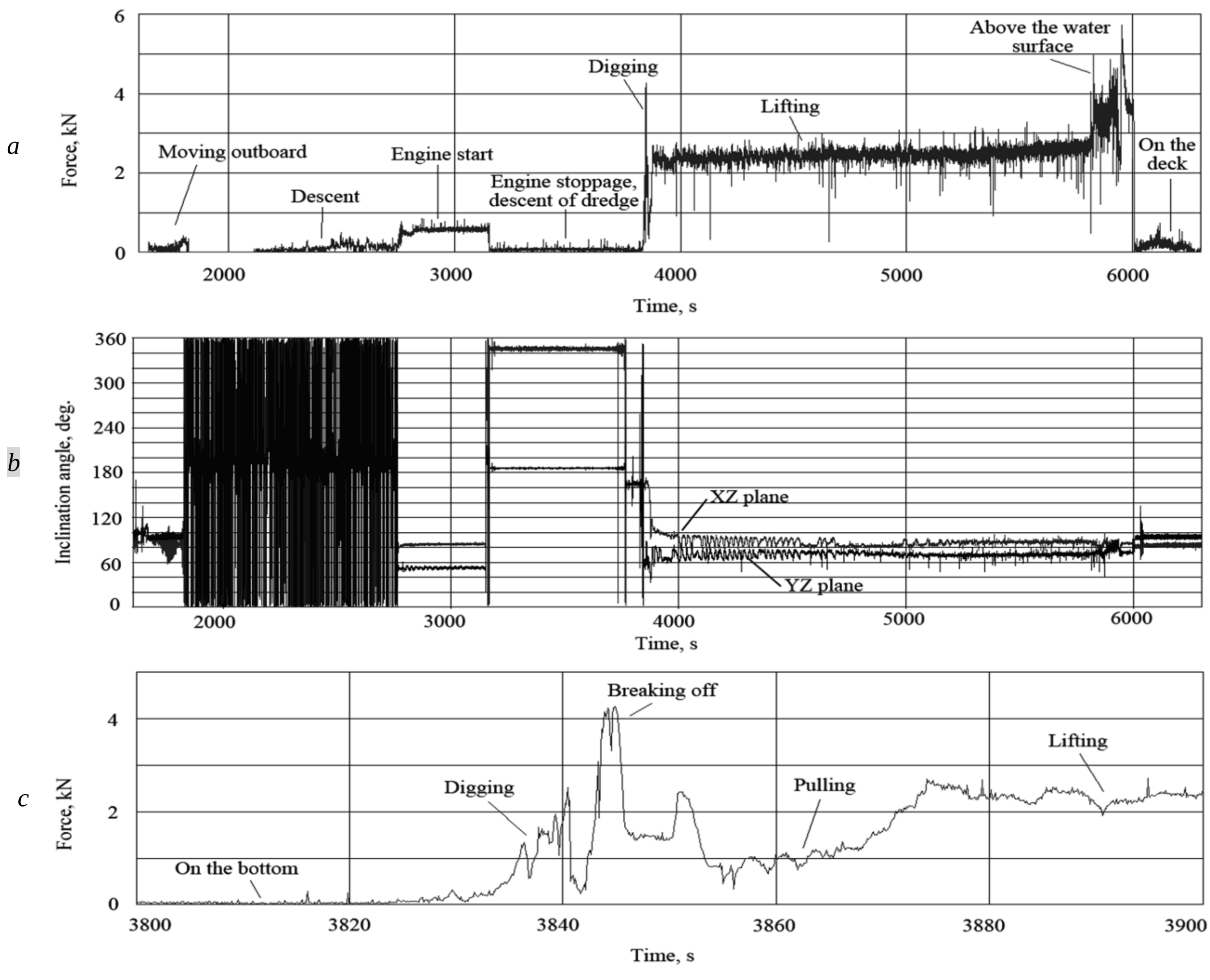

Fig. 6. Oscillograms: rope sling force during the dredging cycle (a) and during the digging (c); inclination angle in relation to the horizon (b)

The obtained results converge well with log entries about dredging process operations. On the force oscillogram (fig. 6, *a*), the first peak coincides with the dredge lifting above the vessel deck and its moving outboard with the help of U-frame. Further decline of force is caused by the cable high-speed veering out (about 2m/s), which is comparable with free fall velocity of the dredge in the water as John Mero wrote about it [1]. In this case, the cable force is close to zero. For this time period, from dredge inclination diagram, it is possible to see the complicated kinematics of the dredge during its descent to the bottom. To ensure the dredge digging into the bottom ground, its cutting part is laden, so that free fall of the dredge into water is carried out teeth down. Large screen area of the bucket interior helps to hold it in such position. At a low vessel speed (about 0,3mph), the dredge moved down with various inclinations as can be seen from the graphs (fig. 6, *b*).

Dredging should be done at 2–3mph vessel speed. In condition of slow vessel drift, the engine was started in order to drive the ship propeller. Therefore, the second peak on the force oscillogram is connected with the cable tension increase through hydrodynamic resistance due to the dredge moving underwater when the vessel speed changes from 0.3 to 3.0mph. Further drop of the dredge with 2m/s speed occurred with inclination to the horizon but in teeth up position. Rope sling force at that moment was 0.6kN (the hauling cable force was calculated by vector addition of rope sling forces and was 1.15kN).

The next peak on the force oscillogram corresponds to soil digging. According to inclination oscillogram, the dredge was laid on the bottom at an angle to the horizon a bit smaller than 15° and remained in that position until the hauling cable was strained. When the dredge was laid on the bottom, the cable was still being veered out which probably led to formation of a loop around the dredge. As the cable got strained, the loop got tightened, which led to a single dredge rollover relative to the cutting edge, which supposedly led to the cable entangling.

The length of the rope sling without sensor became smaller because of cable fouling near the swivel. This circumstance led to the complication of calculations to determine the tensile force of the hauling cable. In order to define the latter one, the comparison of tension sensor readings with the weight of the dredge lifted above the water was made. Here, the degree of the dredge filling was taken into account (coccolith took 50% of its volume, water being the rest). The result was a correction factor that allowed determining the tension of the hauling cable depending on indications of the force measuring equipment.

Of particular interest is determination of resistance to digging including the ground cutting, bucket loading and bucket friction forces. This requires defining hydraulic resistance at the moment of ground digging. From the dredge inclination and acceleration oscillograms (fig. 5, 6), it was found that digging process lasted less than 10 s. For this interval of time, we built acceleration-time characteristic (fig. 7, *a*), which allowed to determine hydraulic resistance by methods described in [1]. The tractive effort diagrams and hydrodynamic resistance are shown in fig. 7, *b*. The digging force (in fig. 7, *b*) was determined by subtracting the hydrodynamic resistance from the tractive effort at the corresponding time moments.

a

b

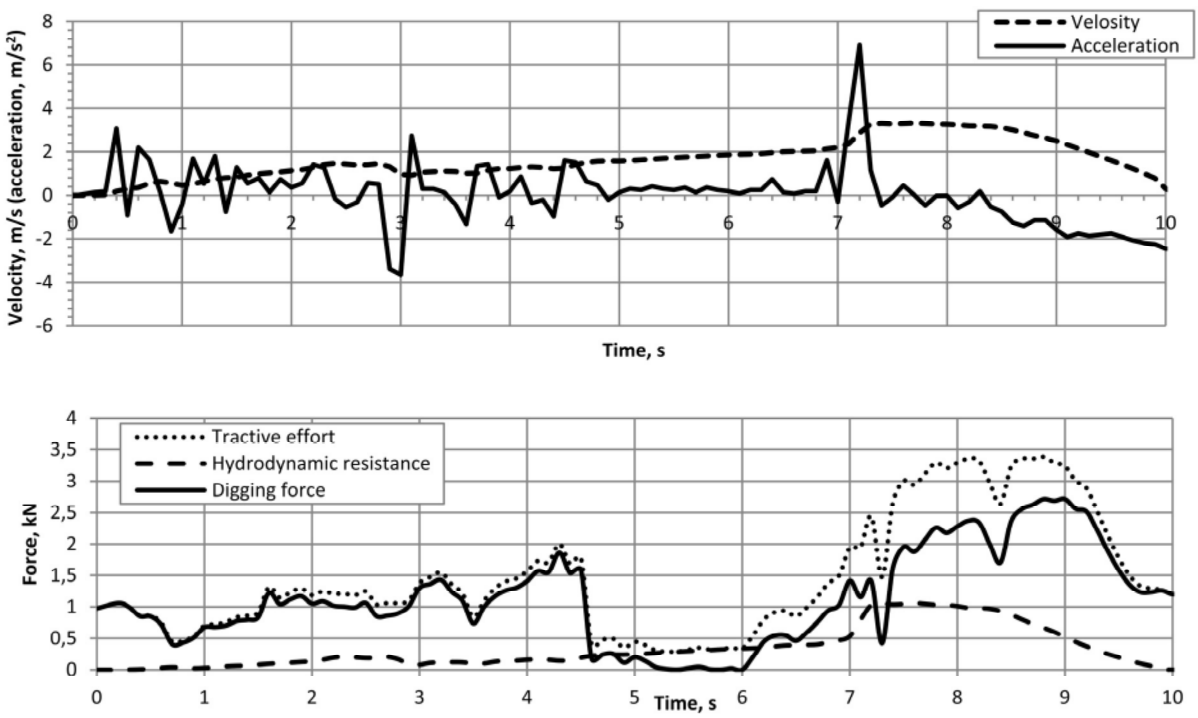

Fig. 7. Diagrams of velocity, acceleration (a) and forces (b) during the digging cycle

After the dredge reached the bottom, the vessel continued to move along the course at 3mph. When the tension force of the hauling cable exceeded 0.1kN, the dredge started to move with non-uniform acceleration. During the first 7.5s, its speed increased from 0 to 3.3m/s and then, during the next 3s, dropped to 0. The dredge was moving nonuniformly with periodical burying into the ground at no more than 30° to the horizon (mostly 10–15°) during digging process. The dredge heeling was 5–7° in that time period. The maximal tractive effort attained 3.4kN, the digging force (without hydrodynamic resistance) – 2.7kN. The obtained values the tractive force are compatible with those at flood bypass mining with scraper equipment [2, 3]. This confirms the marginal impact of hydrostatic pressure during the waterlogged ground digging [4].

The dredge was pulled along the bottom with inclination 35–45° after the digging process and then it was lifted up to the vessel with 80–85° to the horizon. The Hauling cable force varied slightly and was about 2,0kN when the dredge was being lifted. The Hauling cable force rose sharply to 4.5kN when the dredge had been lifted above the water surface. It was caused by the termination of the Archimedes force, as well as dynamic loads arising due to the vessel roll. After the water drained out through the holes in the dredge walls, the tension of the cable reduced to 2.7kN and then fell to zero when the dredge had been lowered onto the ship's deck.

Laboratory tests of the coccolith sediments samples, taken within the experimental area of the Black Sea with geological tube, allowed defining some physical and mechanical properties. Investigations of samples were carried out in accordance with State Standards [5–7]. Research results are as follows: density – about 1200kg/m^3, humidity – 226%, soil adhesion – 480Pa.

Singling out ground cutting and bucket loading forces from the total digging force is of practical interest. It requires subtracting of hydrodynamic resistance and bucket friction force from the tractive effort.

In R&D Institute "Okeanmash", investigations of resistance to movement of deep-sea machines supporting parts were carried out. The „sledge" model (fig. 8) was used for the tests. The model with 31kg mass was brought on to the bottom (Nizne-Chubashsky tailing dump, the Kerch Peninsula) with 0,05m/s velocity. The tensile force of the pulling cable had been measured. The bottom of the trial polygon was presented by argillaceous sediments of the following properties: density – 1180–1330kg/m^3; adhesion – 0.2–0.7kPa; humidity – 187–262%; bearing power – 1.1–4.0kPa. The maximal tractive effort was 330N.

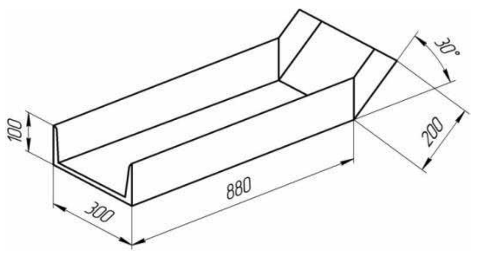

Fig. 8 General view of the „sledge" model

Comparing the conditions of experimental research on the experimental plot in the pond and those in the Black Sea, the range of resistance to movement of the dredge may be determined in the first approximation. From the authors' point of view, it should be no more than 500–800N. Thus the maximum ground cutting and bucket loading forces did not exceed 1.9–2.2kN during sampling sediments at the station 18/73.

Conclusions. In spite of relative simplicity of dredging equipment in terms of design, operation and maintenance, deep-sea dredging process is quite complicated. First of all, it is connected with necessity to execute remote operations of ground digging at great depths without the possibility to control sampling equipment. Therefore the development of dredging technology recommendations based on theoretical and experimental investigations as well as creating tools for tracking the dredge kinematics in real time will improve the efficiency of dredging.

Research results reveal that during lowering of scraper dredge to the sea bottom with the cable veering out at a speed 2–2,5m/s and at a low vessel speed (0.3–0.5mph), the complicated kinematics of dredge is connected with its unstable position in space. It can lead to premature failure or losing of sampling equipment due to kinking and tangling of the cable and its clinging to dredge's projecting parts. So at the low speed of the vessel (less than 0.5mph), lowering of the dredge to the bottom should be done at velocity less than 2m/s.

The digging force of loose waterlogged ground at 1885m depth under water is commensurable to the one at flood bypass mining conduits with scraper equipment. Thus, the results of field tests confirm the scientific principle about the marginal impact of hydrostatic pressure while digging waterlogged ground. Maximal traction force of coccolith sediments sampling at the station 18/73 was 3.4kN. According to the calculation, the balance of hydrodynamic resistance was almost 30%, the share of the ground cutting and bucket loading forces – 65%, resistance to the movement of the dredge at the bottom – about 5% (on a site with low-acceleration). The very process of digging the ground was non-uniform and jerky. Overall duration of digging was less than 10 s while the duration of dredging was more than 1, h.

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Мета. Дослідження процесу глибоководного драгування на основі результатів експериментів, проведених у 73-му рейсі науково-дослідницького судна „Професор Водяницький“ під час експедиції в Чорному морі 7–17 червня 2013 р.

Методика. Експериментальні дослідження були проведені із залученням канатно-ковшового обладнання науково-дослідницького судна „Професор Водяницький“, що застосовується для відбору проб донних відкладень. При цьому було використано розроблене в Національному гірничому університеті тензометричне та акселерометричне вимірювальне обладнання, що встановлюється на ґрунтозабірний пристрій. Експеримент проведений при відборі проб органо-мінеральних відкладень скреперною драгою з глибини 1885м.

Результати. Отримані осцилограми, що дозволяють простежити кінематику та динаміку скреперної драги при відборі проб донних відкладень. Встановлені несприятливі режими роботи добувного обладнання, при яких спостерігається нестабільне положення у просторі ґрунтозабірного пристрою під час його опускання на дно. Визначені зусилля копання органо-мінеральних відкладень драгою місткістю 0,33м^3. У результаті натурного експерименту підтверджено положення щодо незначного впливу гідростатичного тиску на зусилля копання при розробці пористих водонасичених середовищ.

Наукова новизна. Встановлені в ході експерименту робочі навантаження на виконавчий орган ковшового типу дозволяють провести верифікацію деяких положень теорії різання водонасичених ґрунтів в умовах дії високого гідростатичного тиску на основі даних натурних досліджень.

Практична значимість. Результати експериментальних досліджень можуть бути використані для обґрунтування параметрів виконавчих органів ковшового типу глибоководних ґрунторозробних машин. Виключення виявлених несприятливих режимів роботи канатно-ковшового обладнання науково-дослідницького судна „Професор Водяницький“ дозволить знизити ймовірність виникнення аварійних ситуацій при проведенні пробовідбірних робіт.

Ключові слова: *драгування, скреперна драга, органо-мінеральні відкладення, глибоководний видобуток*

Цель. Исследование процесса глубоководного драгирования на основе результатов экспериментов, проведенных в 73-м рейсе научно-исследовательского судна „Профессор Водяницкий“ во время экспедиции в Черном море 7–17 июня 2013 г.

Методика. Экспериментальные исследования были проведены с задействованием канатно-ковшового оборудования научно-исследовательского судна „Профессор Водяницкий“, применяемого для отбора проб донных осадков. При этом было использовано разработанное в Национальном горном университете тензометрическое и акселлерометрическое электроизмерительное оборудование, устанавливаемое на грунтозаборном устройстве. Эксперимент проведен при отборе проб органо-минеральных осадков скреперной драгой с глубины 1885м.

Результаты. Получены осциллограммы, позволяющие проследить кинематику и динамику скреперной драги при отборе проб донных осадков. Установлены неблагоприятные режимы работы добычного оборудования, при которых наблюдается нестабильное положение в пространстве грунтозаборного устройства во время его опускания на дно. Определено усилие копания органо-минеральных осадков драгой вместимостью 0,33м^3. В результате

натурного эксперимента подтверждено положение о малом влиянии гидростатического давления на усилие копания при разработке пористых водонасыщенных сред.

Научная новизна. Установленные в ходе эксперимента рабочие нагрузки на исполнительный орган ковшового типа позволяют произвести верификацию положений теорий резания водонасыщенных грунтов в условиях действия высокого гидростатического давления на основе опытных данных натурного эксперимента.

Практическая значимость. Результаты экспериментальных исследований могут быть использованы для обоснования параметров исполнительных органов ковшового типа глубоководных грунторазрабатывающих машин. Исключение выявленных неблагоприятных режимов работы канатно-ковшового оборудования научно-исследовательского судна „Профессор Водяницкий“ позволит снизить вероятность возникновения аварийных ситуаций при проведении драгировочных работ.

Ключевые слова: *драгирование, скреперная драга, органо-минеральные осадки, глубоководная добыча*

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