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Research on Rigging Equipment for Ship Retrieval from a Lake

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Abstract
To protect the ecosystem of Lake Khuvsgul and eliminate hazardous waste, the Government of Mongolia undertook the recovery of the sunken Sükhbaatar ship. This study presents the engineering design, analysis, and application of rigger equipment used in the retrieval process, with a particular focus on the calculation, selection, and deployment of steel wire ropes to generate the required pulling force. The Sükhbaatar ship, constructed in the former Soviet Union in 1956, measured 43.3 meters in length, 8.4 meters in width, and 11.4 meters in height (including the antenna), with a hull height of 5.7 meters, a total weight of 309 tons, and a cargo capacity of 400 tons. After sinking in 1985, the vessel was successfully retrieved during a 37-day operation conducted from October 1 to November 7, 2021. The recovery was executed using a combination of pulling and lifting forces generated by specialized rigging systems, including winches, pulleys, and steel wire ropes, under challenging environmental and operational conditions.

Keywords: steel wire rope, winch, pulling force, pulley system, shackle

Introduction

As part of a national effort to preserve the ecosystem of Lake Khuvsgul, remove hazardous waste from the lakebed, and mitigate pollution, a comprehensive engineering study was undertaken to support the retrieval of the Sükhbaatar ship, which sank in 1985. The operation was conducted on-site and guided by detailed technical calculations, an engineering study, and a phased technological workflow. The project was initiated with the understanding that the Sükhbaatar ship, assembled at Khankh Port in 1956, had served for three decades in maritime transport and held historical significance as Mongolia's second official vessel [1, 2, 3].

At the time, Mongolia had no previous experience or documented methodology for salvaging a sunken, heavy-weight ship from inland or open waters. The cause of the sinking remained unidentified, and no theoretical or engineering research had been previously conducted. There was an absence of technical planning, modeling, or simulation regarding the recovery of a submerged structure with an estimated mass of up to 1,200 tons under cold-climate conditions, where pulling and lifting operations required accounting for frictional resistance and sliding forces both underwater and on land [1, 2, 3].

To address these challenges, the project team conducted an extensive review of international salvage operations. This included evaluating engineering solutions, materials, structural components, and technical procedures employed in similar recovery efforts. Based on these findings, the team developed multiple retrieval scenarios, technical strategies, planning documents, and mechanical calculations tailored to the context of Lake Khuvsgul.

The recovery of the Sükhbaatar ship was ultimately structured into four distinct technological phases: (1) towing the ship to shallower waters (designated as the red phase), (2) rotating the vessel to an upright position (yellow phase), (3) pumping out internal water to enable refloating (blue phase), and (4) transferring the ship to a designated onshore location (green phase). This paper presents the detailed engineering calculations, selection criteria, and operational parameters for the steel wire ropes used throughout these phases. A safety checklist was also developed and implemented to ensure the reliable and secure performance of all rigging equipment involved in the operation.

Methods

Ship retrieval experiment

According to our preliminary calculations, the estimated weight of the ship was 821.07 tons. We created a 1:100 scale model and planned a series of experiments based on the ship's position in the water, lake depth, shoreline conditions, lakebed characteristics, and coastal infrastructure. The experiment was conducted by positioning the ship in multiple arrangements and applying loads at different points. The following image illustrates a test where a load was attached to the knecht located at the bow of the ship (Point 1) and then pulled. During the test, a sliding/ tilting motion of the ship's stern toward the deeper part of the lake was observed. The applied load weight during the experiment ranged between 160 and 200 grams. When a load was attached and pulled from the knecht located at the midsection of the ship (Point 2), a rotational movement in the opposite direction of the counterclockwise along the ship's length was observed. The applied load weight during this test ranged between 310 and 380 grams.

Additionally, when a load was attached and pulled from the knecht at the stern of the ship (Point 3), the bow section showed a sliding motion toward the deeper part of the lake. The applied load weight during this test ranged between 240 and 270 grams.

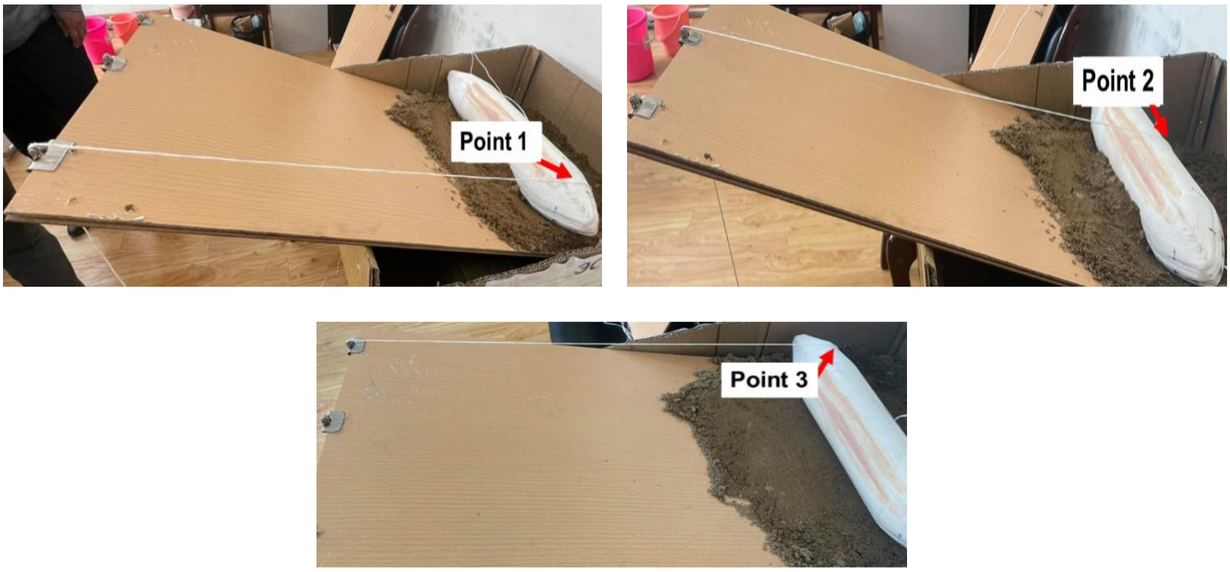

Figure 1. Position of the bow section (point 1), midsection (point 2), and stern (point 3) during the test

Preliminary calculations for steel wire ropes and pulley system

As previously mentioned, the estimated weight of the ship was 821.07 tons**.** An initial field survey indicated the availability of three 15-ton winches**,** and based on this information, the retrieval operation was planned using steel wire ropes attached to Points 1, 2, and 3 of the ship, with each winch providing 15 tons of pulling force**.**

By distributing the pulling force across three points, the estimated load per point was 274 tons. Using this load, the required mechanical advantage of the pulley number was calculated as 18.26 using the following formula.

$$m = P_0 / P \cdot \eta \qquad (1)$$

where: P is the force acting on the pulley system, P_0 is the total pulling force, η is the friction coefficient of the pulley system.

Studies show that pulley systems designed to lift 10–16 tons typically have a range between 2 and 3. However, our calculation resulted in 18.26, making it impractical to design and manufacture. From this, we determined the diameter of the steel wire rope based on the tensile strength condition, considering the allowable stress [σ_{rope}] = 1800 MPa [23] and the force Fmax = 831 tons.

$$\sigma_{ten} = \frac{F_{ten}}{A} = \frac{4F_{ten}}{\pi d^2} \leq [\sigma_{ten}] \quad (2)$$

$$d \geq \sqrt{\frac{4F_{ten}}{\pi[\sigma_{ten}]}} \quad (3)$$

The calculation of a steel wire rope diameter d_{min}=145.71 mm.

Additional calculation for steel wire rope and pulley system

During the process of pulling the ship, additional calculations for the pulley system were performed within the options for mechanisms and equipment such as winches, pontoons, and bulldozers that can be procured and used. The estimated weight of the ship was taken as 821.07 tons for the calculations. Option one: The ship will be pulled using three winches with a capacity of 5 tons each, ten pontoons with a capacity of 35 tons each, and a bulldozer with a power of 335 kW. If the pulley number is taken as 3, then a single winch alone can pull a load of 15 × 3 = 45 tons, and the three winches together will pull a total load of 135 tons (see Figure 2).

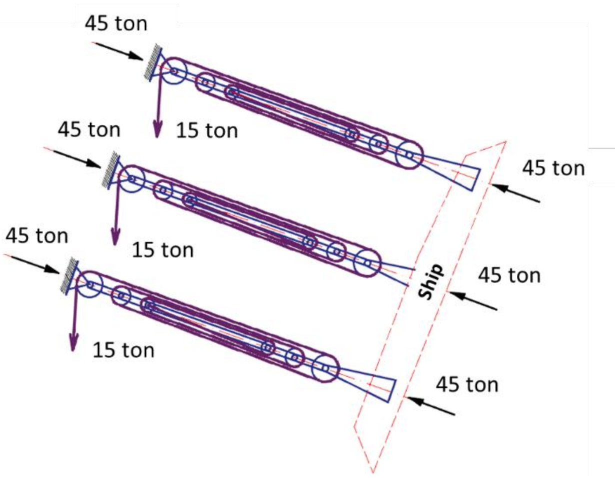

Figure 2. Load scheme for pulling with three 15 ton winches

The ten pontoons, each with a capacity of 35 tons, will lift a total load of 350 tons. And our calculations showed that 14 bulldozers with a power of 335 kW are needed. The length of the steel rope is calculated as the pulley number is 3, and the length of a single branch of the rope for the three winches is 110 m, the total rope length is 3*3*110=990 m. The total rope reserve on the three winch drums 3*12=36 m, and the fastening length is 3*4=12 m. The 14 bulldozers results in a total rope length of 180*14=2520 m. Thus, the overall total rope length is 990+36+12+2520=3558 m.

Option two: The ship will be pulled using three 30-ton winches, ten 35-ton pontoons, and bulldozers with 335 kW power. If the pulley number is taken as 4, then a single winch can pull 30*4=120 tons, meaning that the three winches together will pull a total of 360 tons (see Figure 3).

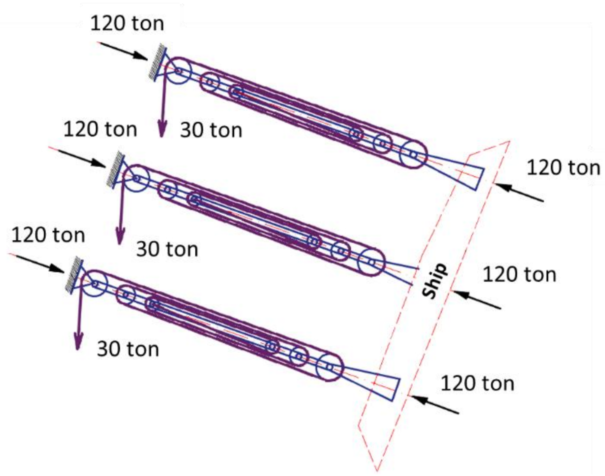

Figure 3. Load scheme for pulling with three 30 ton winches

The ten pontoons, each with a capacity of 35 tons, will lift a total of 350 tons. When determining the required number of bulldozers with a power of 335 kW, it was found that 6 bulldozers are needed. The required steel rope length is determined as follows.

Assuming the pulley number is 4 and the length of a single branch of the rope for the three winches is 110 m, the total rope length is 4*3*110=1320 m. The total rope reserve on the three winch drums is 3*12=36 *m, and the fastening length is* 3*4=12 m. The 6 bulldozers each require 180 m, resulting in a total bulldozer rope length of 180*6=1080 m. Thus, the overall total rope length is 320+36+12+1080=2448 m.

Option three: The ship will be pulled using only three 50-ton winches. If the pulley number is 6, then a single winch can pull 50*6=300 tons, meaning that the three winches together will pull a total of 900 tons (see Figure 4).

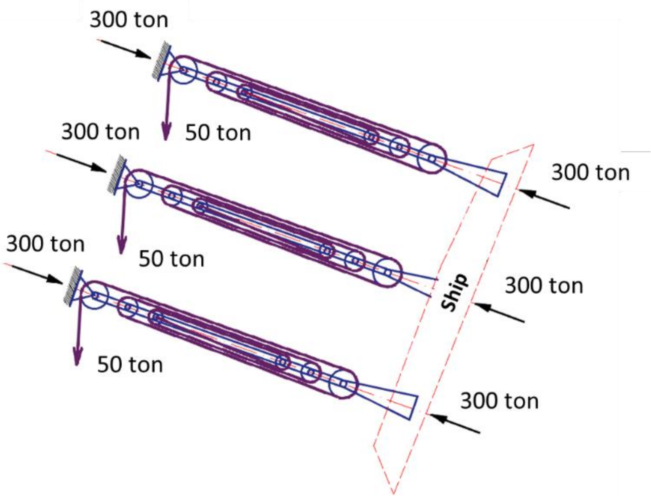

Figure 4. Load scheme for pulling with three 50 ton winches

The three 50-ton winches will fully pull the given load. The required steel rope length is determined as follows. Assuming the pulley number is 6 and the length of a single branch of the rope for the three winches is 110 m, the total rope length is 6*3*110=1980 m. The total rope reserve on the three winch drums is 3*12=36 *m, and the fastening length is* 3*4=12 m. Thus, the overall total rope length is 1980+36+12=2028 m.

From the given equipment in the calculations, the 15-ton winch and the 335 kW bulldozers can be supplied from domestic resources, while the ten pontoons, 30-ton winches, and 50-ton winches can be purchased through foreign purchases.

Detailed calculation of steel rope and pulley system

Through detailed calculations and research, the total weight of the sunken ship was re-determined to be 1421.58 tons, and an assessment of available domestic resources for technical equipment was conducted.

Based on the technical equipment study, a 25-ton winch for gentle pulling, with additional pulley fittings that allow increasing the number up to 3, a BTS-4 model tracked vehicle designed for pulling, equipped with a built-in scraper to provide support reactions. As well as a 20-ton winch for gentle pulling, with additional pulley fittings that allow increasing number up to 3, mounted on a MAZ-537 model wheeled transport vehicle, were studied and used in the retrieval operation (Figure 5).

Figure 5. BTS-4 Model Tractor and MAZ-537 Model Transporter

During the pulling of the ship, three BTS-4 model tractor and one MAZ-537 model transporter were used. These machines were capable of pulling with a total force of up to 285 tons. During the operation, the pulley system, hooks, steel wire ropes, shackles, spreader bars, and other rig.

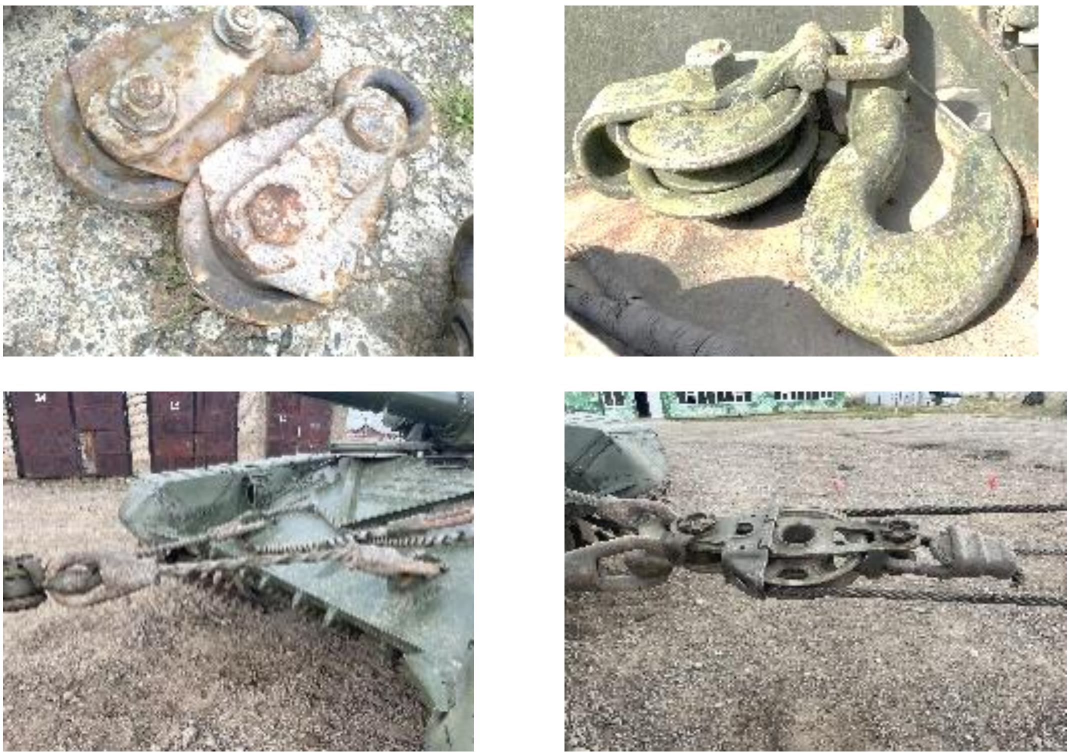

Figure 6. Rigging Equipment of the BTS-4 Model Tractor

An additional steel wire rope was connected to the main pulley system of a single BTS-4 model tractor, which needed to withstand a reaction load of 75 tons. Considering the additional steel wire rope was divided into two strands, each strand bore a load of 75 ÷ 2 = 37.5 tons, or 367,875 N of force. Based on this load, a 27 mm steel wire rope with a breaking strength of 376,000 N was selected according to standards. Since the pulling operation was expected to be performed only a few times, the safety factor (k-coefficient) for the steel wire rope reserve was not considered (Figure 7).

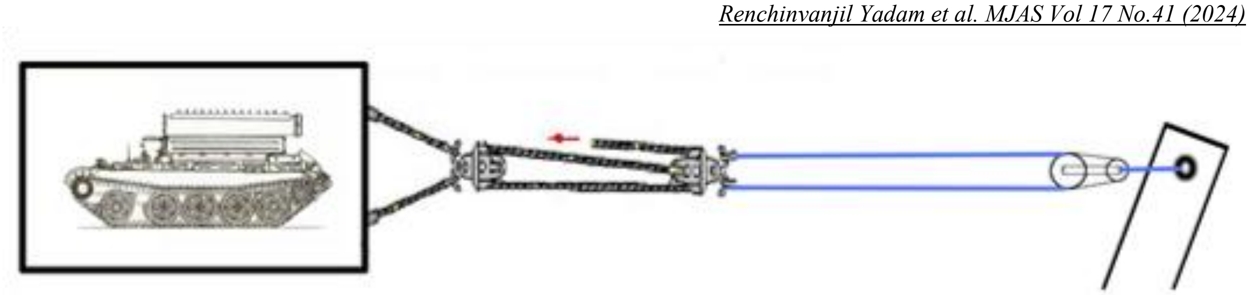

Figure 7. Pulley System of a Single BTS-4 Model Tractor

In this operation, one BTS-4 model tractor and one Kraz-255 model wheeled tractor were used for pulling. The additional steel wire rope needed to withstand a reaction load of 82 tons. Since the additional steel wire rope was divided into two strands, each strand bore a load of 82 ÷ 2 = 41 tons, or 402,210 N of force. Based on this load, a 28 mm steel wire rope with a breaking strength of 408,000 N was selected according to standards. Since the pulling operation was expected to be performed only a few times, the safety factor (k-coefficient) for the steel wire rope reserve was not considered (Figure 8).

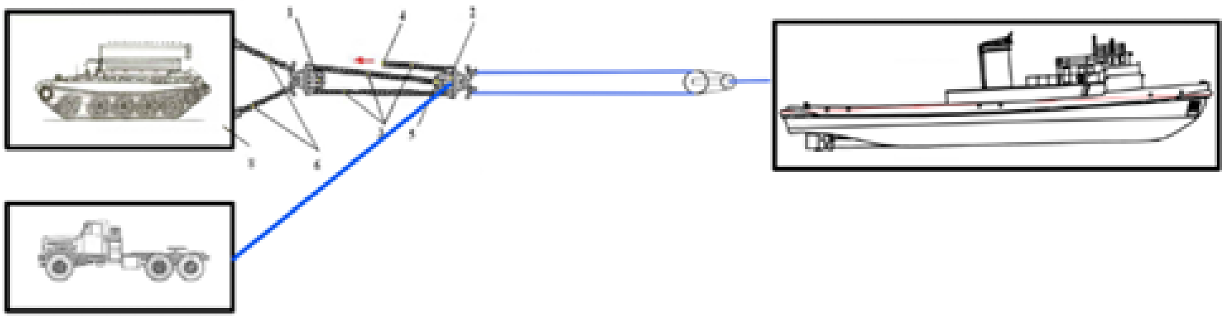

Figure 8. Pulley System of One BTS-4 Model Tractor and One Kraz-255 Model Tractor

Use of steel wire ropes

During the ship retrieval operation, a total of 56 pulling procedures were organized. The pulling process used 3,224 meters of 28 mm diameter steel wire rope**,** 1,250 meters of 21 mm diameter steel wire rope**,** and 325 meters of 18 mm diameter steel wire rope**,** with approximately 200 cuts made according to around 50 different technological requirements**.** In addition, the steel wire ropes were spliced 126 times to prepare for pulling. The nine personnel assigned to work with the BTS-4 unit collectively set up and dismantled the pulley system 315 times. The steel wire ropes used in a single pulling operation could not be re-spliced, and in most cases, they broke on the third pull (Figure 9).

Figure 9. Broken steel wire ropes

The ship retrieval operation was developed in four technological stages: pulling the ship toward the shallow part of the lake (red), raising it to its upright position (yellow), pumping out water to refloat the ship (blue), and positioning the ship on a prepared site onshore (green). To ensure the safety of the pulling equipment, pulley system, and pulling operations, a checklist was developed for each technological stage, and a Health and Safety Inspector monitored the process.

Results and discussion

From the 1:100 scaled-down experiment, it was observed that the force applied from Point 1 at the bow moved the ship with less force compared to the force applied from Point 3 at the stern. The force applied from Point 2 at the midsection was greater than the forces at Points 1 and 3, causing the ship to rotate counter clockwise along its length. Based on the results of this experiment, the initial decision was made to pull the vessel from three points simultaneously (Figure 10) and to alternately pull from Points 1 and 3.

Figure 10. 1:100 scale model of the ship

Each of the 15-ton, 30-ton, and 50-ton units has three winches, ten 35-ton pontoons, and fourteen bulldozers with a capacity of 335 kW each were considered for pulling. However, constructing a structure capable of providing up to 50 tons of reaction resistance was considered impractical due to difficulties in construction, limited space in the pulling environment, purchase delays, and high costs. Based on a study of available domestic resources, equipment capable of generating its own reaction resistance and freely maneuvering within the pulling area was selected. Three BTS-4 tracked tractors equipped with a 25-ton winch and rigging tools, along with one MAZ-537 wheeled transporter equipped with a 20-ton winch and rigging tools, were used for the operation.

A total of 4,799 meters of steel wire ropes with diameters of 18 mm, 21 mm, and 28 mm, along with approximately 50 different technological rigging configurations, were used in the ship retrieval operation. During the process, a total of 538 pulley system setups, 53 repositioning movements, and 56 pulling operations were carried out.

Conclusion

Our team conducted research and calculations for the sunken ship retrieval operation while strictly adhering to occupational safety and health regulations. Based on the available machinery and technical resources in Mongolia, as well as engineering solutions, we developed and approved a technological chart and work sequence. Following this plan, the sunken ship was successfully retrieved to its designated position under professional supervision and organization. This operation was carried out based on a technological plan developed in accordance with the principles of ensuring coordination between government agencies, utilizing the intellectual capacity of Mongolian engineers, scientists, and professors to minimize costs, avoiding unnecessary purchases of materials and equipment from abroad, and making use of the available machinery and equipment in Mongolia.

Conflict of interests

The authors declare no conflict of interests.

Authors' Contribution

Renchinvanjil Yadam, Ulziisaikhan Purevsuren, Naidandorj Radnaa, and Khash-ochir Namjil conducted calculations and studies on steel cables and towing equipment. Khenmedekh Lochin and Ayurzana Badarch carried out research on determining the ship's weight. Gankhulug Tsegmed, Galbadrakh Davaa, and Ider Gombojav conducted a towing experiment and research on the ship

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