Part 3.1: Rope friction tests: Rope on timber

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Purpose of investigation

This series of tests investigates the damage inflicted on a wooden log by a moving hemp rope in the absence of lubrication.

It is well known that substantial wear will occur on the log even under rather small loads usually requiring some form of protection for the log. What is not known is the extent of damage caused by different loads on the rope and the effect of the log's diameter. Both are important system parameters when lowering large loads into position with ropes slung over logs and would have varied between applications in the Old Kingdom.

Test setup and testing process

The test setup and its schematics are shown in fig.1.

The logs were fixed to the strong floor of our lab using a wooden clamp system that prevented them from moving or rotating. Different stone drums were attached to a 20 mm hemp rope via a load cell. At its other end, the rope was fixed to the crane via another load cell.

Using the crane, the rope was pulled up about 1 m, then lowered to its original position. This is called one pull in tab. 1. This process was repeated several times in multiple-pull tests.

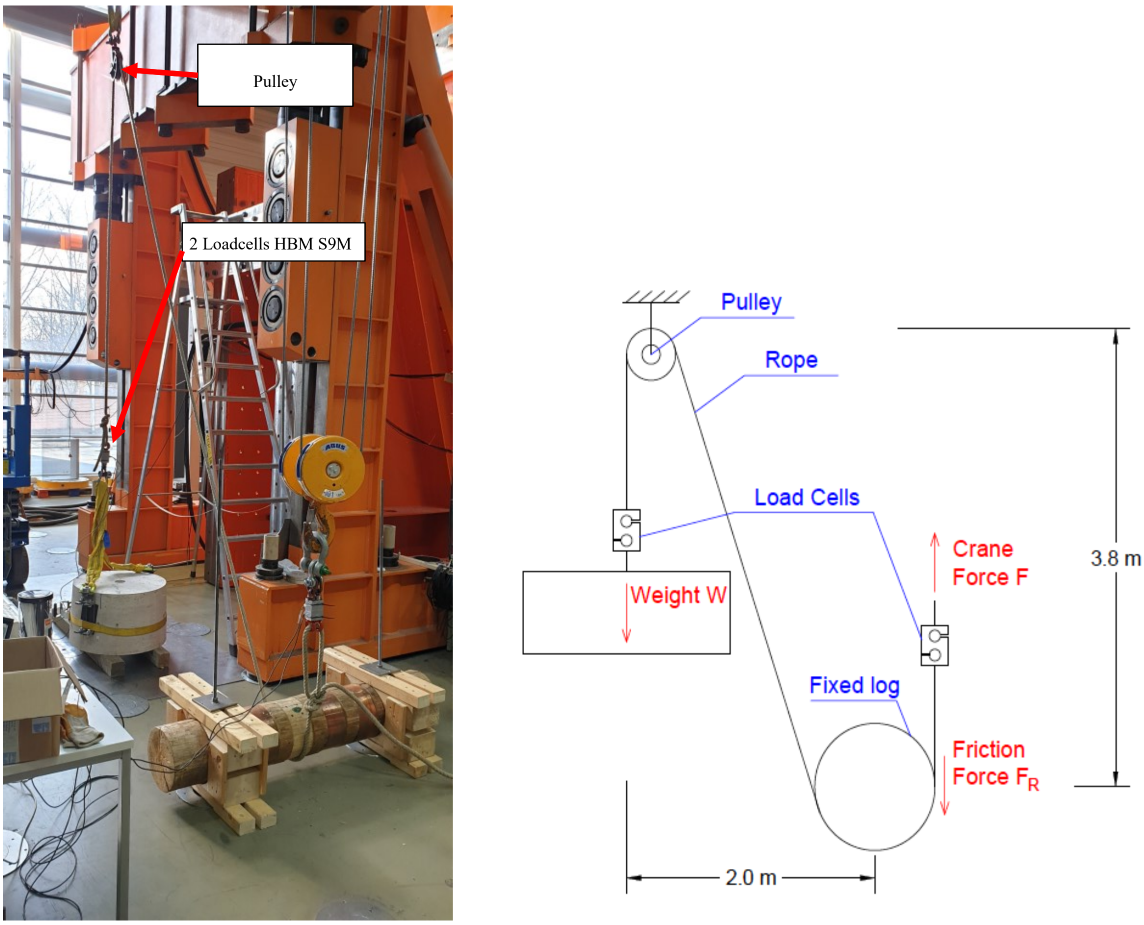


Fig 1. Test setup and its schematics. Stone drums served as weights and the logs were fixed to the strong floor with wooden clamps. Using the crane, the rope was pulled up creating friction on the log. Load cells measured the force on the weight and the one exerted by the crane. (photo by A. Ansalone)

Whenever the weight was changed, the rope was placed in another position around the log and remained there for the following tests.

Rope and timber materials were the same as in the tests with the antechamber replica (see Part 1). The stone drums were of travertine. They were the remains from tests on a scaled column of the Neptune Temple in Paestum, Italy[1].

Measurement and data processing system

To measure the forces, high-resolution load cells (Hottinger Baldwin HBMS9/S9M, range +/- 10 kN, resolution +/- 2 N) were used. Two such load cells were applied in tandem at both ends of the rope (see fig. 1): Thus, channels 8 and 9 measured the force on the weight and channels 10 and 11 on the crane.

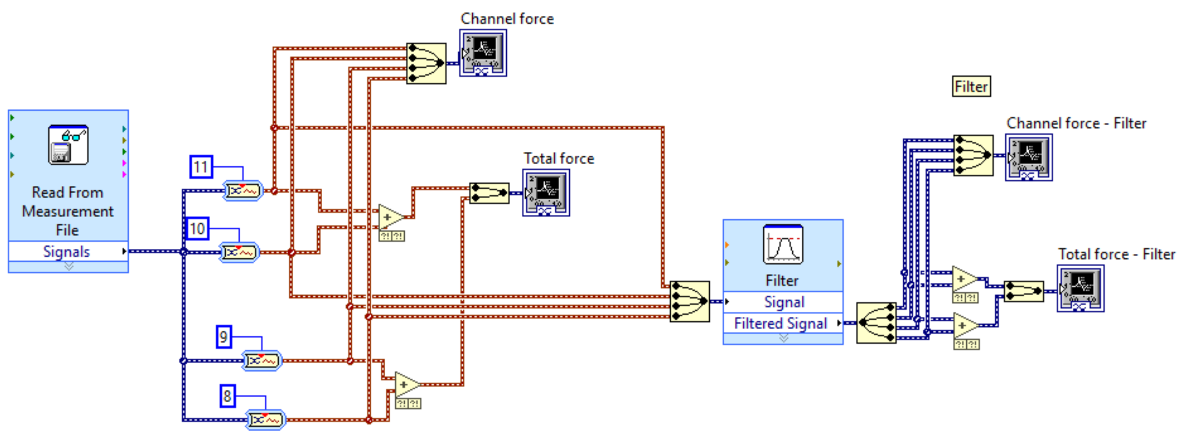


Fig 2. Labview scheme for data processing. Sampling rate was 100 Hz. A Butterworth filter was applied with 0-1 Hz cut-off frequencies. The processed data was charted in real time during the tests.

The loadcells were connected to an Autolog 3000 system[2], where the data was calibrated to represent the forces in Newton. Using Labview[3], the data was then processed with the scheme shown in fig. 2. Data from each test was stored in a separate file. Real-time charts of the processed data were available during testing.

The wear on the log was documented after each test with pictures and movies were taken during the tests. They are available for further scientific studies upon request.

[1] Obón Santacana et al. (2017)
[2] Autolog 3000 Specification
[3] Labview V 2015

Testing program

The testing program is given in tab. 1. Three different log diameters (30 cm, 20 cm and 10 cm) were used in combination with three weights (116 kg, 330 kg and 540 kg).

We started with two single-pull tests whenever the logs or the weight was changed. This was followed by several tests with 5 pulls each and the rope in the same position around the log to allow wear to accumulate.

Tab. 1. Testing program. Pulling the rope up and lowering it again counts for one pull.

Test no.	Diameter cm	Weight kg	No. of pulls	Data file
1	30	330	1	Test_20-02-12_1334_001.txt
2		330	1	Test_20-02-12_1414_001.txt
3		540	1	Test_20-02-12_1546_001.txt Test_20-02-12_1552_001.txt
4		540	1	Test_20-02-12_1601_001.txt
5		540	5	Test_20-02-12_1608_001.txt
6		330	5	Test_20-02-12_1625_001.txt
7		330	5	Test_20-02-12_1631_001.txt
8		116	2	Test_20-02-13_1028_001.txt
9		116	1	Test_20-02-13_1034_001.txt
10		116	5	Test_20-02-13_1040_001.txt
11		116	5	Test_20-02-13_1045_001.txt
12		116	5	Test_20-02-13_1051_001.txt
13	20	116	1	Test_20-02-13_1706_001.txt
14		116	1	Test_20-02-13_1714_001.txt
15		116	5	Test_20-02-13_1718_001.txt
16		116	5	Test_20-02-13_1723_001.txt
17		116	5	Test_20-02-13_1730_001.txt
18		330	1	Test_20-02-13_1750_001.txt
19		330	1	Test_20-02-13_1754_001.txt
20		330	5	Test_20-02-13_1759_001.txt
21		330	5	Test_20-02-13_1805_001.txt
22		540	1	Test_20-02-14_0942_001.txt
23		540	1	Test_20-02-14_0945_001.txt
24		540	5	Test_20-02-14_0950_001.txt
25		540	5	Test_20-02-14_0959_001.txt
26	10	116	1	Test_20-02-14_1221_001.txt
27		116	1	Test_20-02-14_1226_001.txt
28		116	5	Test_20-02-14_1229_001.txt
29		116	5	Test_20-02-14_1234_001.txt
30		116	5	Test_20-02-14_1239_001.txt
31*		330	1	Test_20-02-14_1302_001.txt
32*		330	1	Test_20-02-14_1319_001.txt
33*		330		Test_20-02-14_1406_001.txt
34		330	5	Test_20-02-14_1409_001.txt
35		330	5	Test_20-02-14_1414_001.txt
36		540	1	Test_20-02-14_1430_001.txt
37		540	1	Test_20-02-14_1436_001.txt
38		540	5	Test_20-02-14_1442_001.txt
39*		540	4	Test_20-02-14_1454_001.txt

* One load cell broke in test 31. It was noticed during test 32 and repaired for test 33.
The rope broke in test 39. Therefore, these tests are not suitable for further processing.

Tab. 2 summarizes the number of pulls under each weight. This is approximately equal to the distance in meters travelled by the rope back and forth in one position.

Tab. 2. Number of pulls with the rope in one position

Weight (kg)	30 cm log	20 cm log	10 cm log
116	18	17	17
330	12	12	12
540	7	12	11

Test results

The forces F (crane force) and W (weight force) followed a typical pattern during all single-pull tests. This is exemplified in figs. 3-5 for the three log diameters (30 cm, 20 cm and 10 cm) and weights (116 kg, 330 kg and 540 kg). The friction force F_R is calculated as the difference between the crane force F and weight force W (compare Fig 1.):

$$F_R = F - W$$

During the preparatory phase (see Fig. 3), the weight was lifted off the ground and its initial rotation stabilized. Pulling commenced afterwards with no rotation observed on the weight.

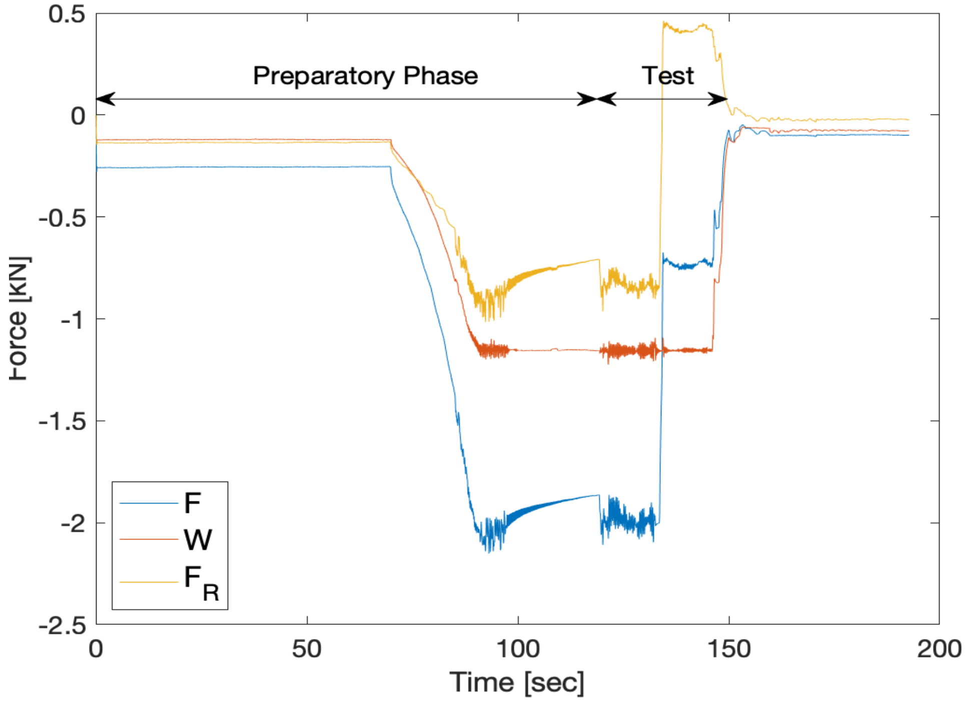


Fig 3. Development of forces F, W and F_R during test 13 (30 cm log, 116 kg, 1 pull)

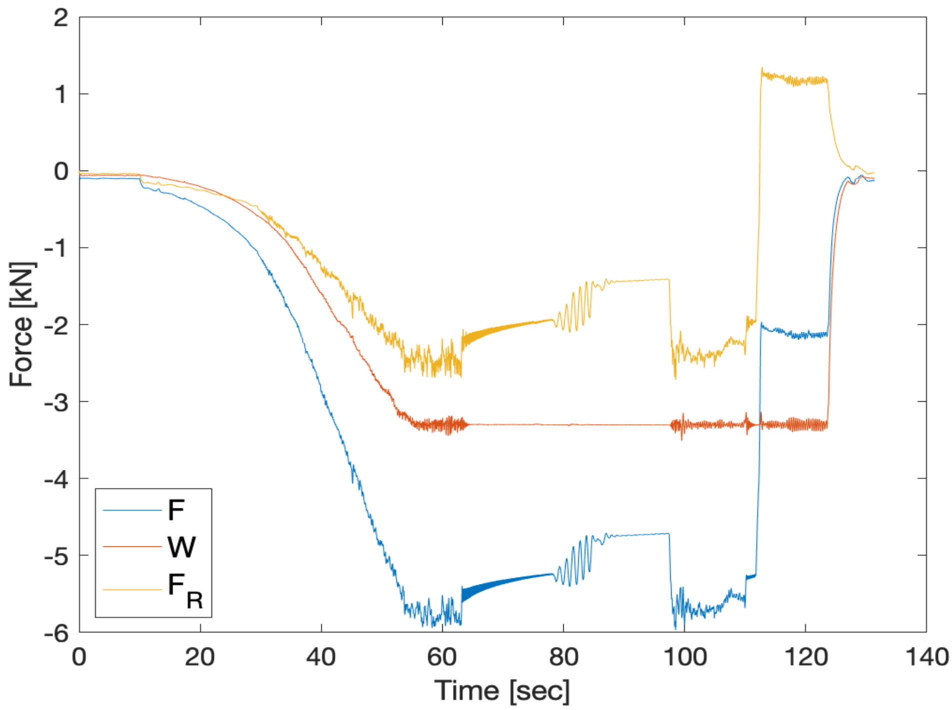


Fig 4. Development of forces F, W and F_R during test 18 (20 cm log, 330 kg, 1 pull)

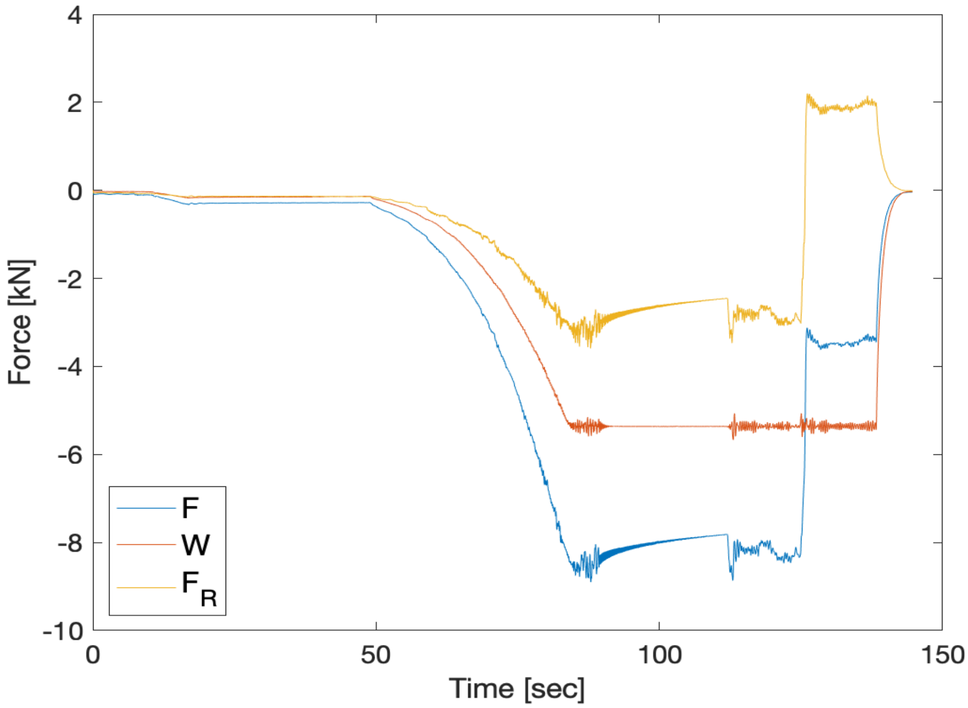


Fig 5. Development of forces F, W and F_R during test 37 (10 cm log, 540 kg, 1 pull)

During multiple-pull tests, the single-pull force pattern repeated (figs. 6 and 7) and F_R increased with each pull. This increase was stronger with small log diameters and larger weights as a result of growing wear on the log.

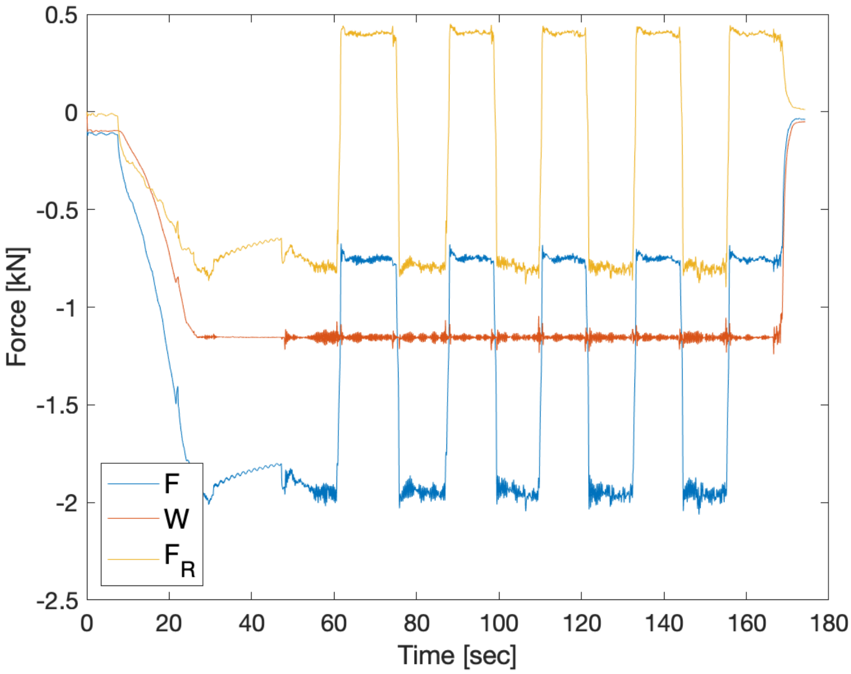


Fig 6. Development of forces F, W and F_R during test 10 (30 cm log, 116 kg, 5 pulls)

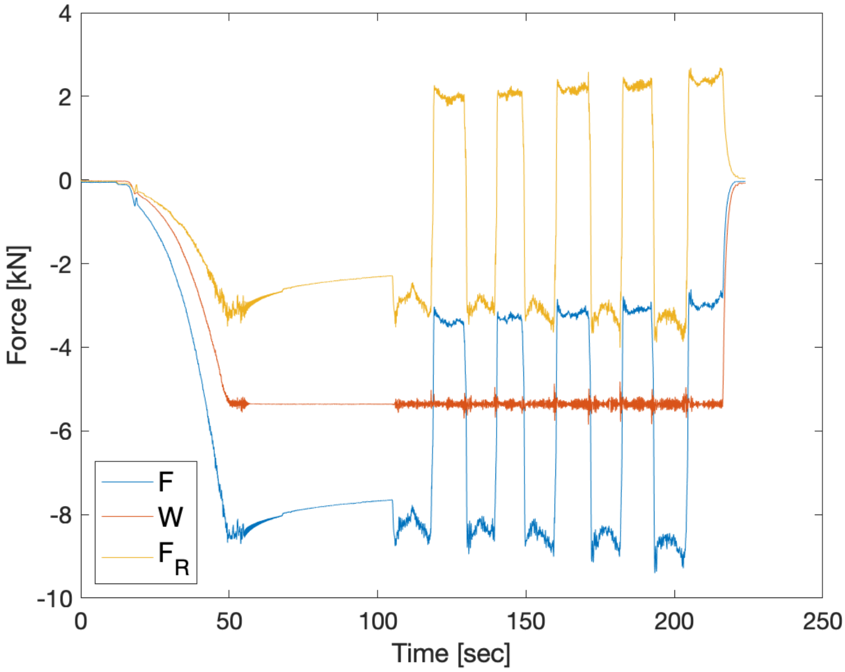


Fig 7. Development of forces F, W and F_R during test 38 (10 cm log, 540 kg, 5 pulls)

As expected, the friction forces change with the applied weight. A coefficient of friction

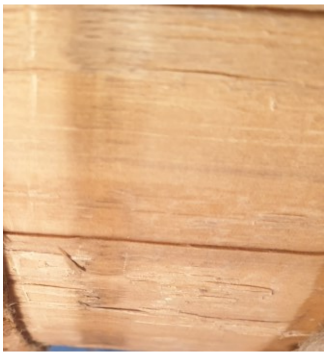
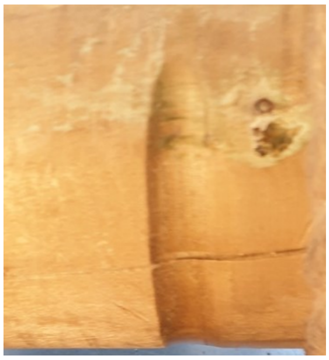
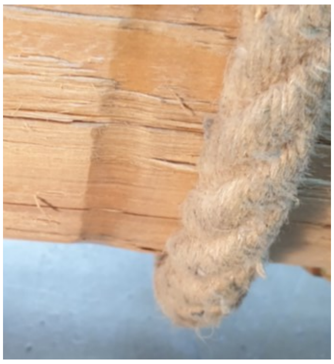
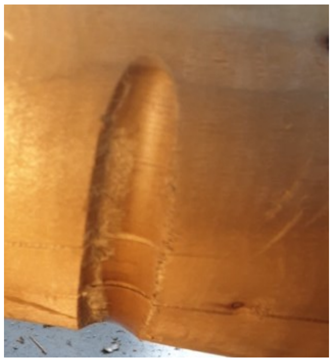
$$\mu = F_R / W$$

ranging from 0.6 to 0.8 was identified when the rope was moving (see Tab. 2). It depended on the wear but not on the diameter of the log.

There was some wear on the rope, but not as significant as the wear on the logs.

Tab. 3 shows the wear on the logs under each weight after the first single-pull tests and tab. 4 at the end of testing. The scarp produced by the rope has a width of approximately 20 mm, which is the diameter of the rope.

Tab. 3. Wear after first single-pull tests (photos by A. Ansalone)

Weight (kg)	30 cm log	20 cm log	10 cm log
116	 After 2 pulls*		
330			
540			

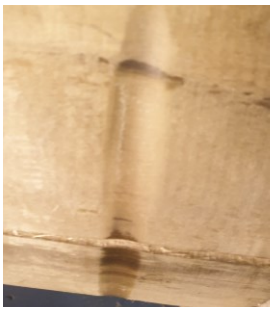
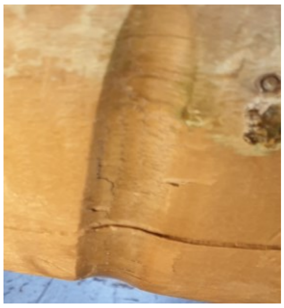
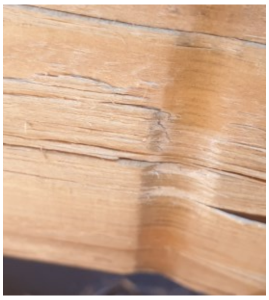
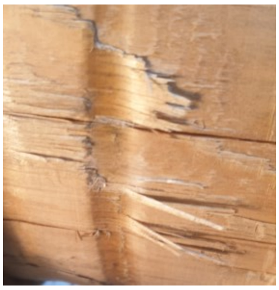
*with 2 subsequent pulls performed in test 8 (tab. 1), no picture is available here for a single pull.

Already under a very low weight (116 kg), even the large log experienced immediate damage. The wood fibres were indented severely and some of them already started to spall off. With larger weights and smaller logs, this initial damage became more pronounced.

Note the blackening especially on the 20 cm log: The friction created enough heat to burn the wood locally.

There was always a very loud noise during operation similar to a jack hammer. Verbal communication with others was only possible within a about a meter’s distance.

Tab. 4. Final damage (photos by A. Ansalone)

Weight [kg]	30 cm log	20 cm log	10 cm log
116	After 18 pulls: 	After 17 pulls: 	After 17 pulls: 
330	After 12 pulls: 	After 12 pulls: 	After 12 pulls: 
540	After 7 pulls: 	After 12 pulls: 	After 11 pulls: 

After pulling the rope back and forth for some 12 m to 18 m, severe scarping was observed in all cases rendering the logs unusable. In the most severe cases (10 and 20 cm log under 540 kg), the rope literally sawed into the log until the log's fibres severed the rope at the end of test 39.

The noise intensified with growing damage. The blackening also grew delivering a scent of burnt hemp and wood fibres.

Conclusions

Even when pulling small weights with ropes over large diameter logs, there is instant damage to the logs and the noise is deafening. For larger weights and smaller logs this intensifies to the point that the rope cuts into the log and destroys it before rupturing itself.

Such damage has been observed on a construction log in the Meidum Pyramid (fig. 8), which allows the conclusion that the cause was a moving rope pulling a large weight.

Fig. 8. Damage on a construction log in the Meidum Pyramid caused by a moving rope (photo by U. E. Dorka)

As expected, these tests have demonstrated clearly that it is not feasible to run ropes over unprotected logs. A fact that Old Kingdom builders were certainly aware of.

References

Autolog 3000 Specification. http://www.peekel.de/download/Autolog3000.pdf [Accessed on 09.07.2020]

Labview Version 2015 Download. https://www.ni.com/de-de/support/downloads/software-products/download.labview.html#306324 [Accessed on 09.07.2020]

Obón Santacana, F., Dorka, U.E., Nguyen, C.K.L., Petti, L. (2017). Behavior of Greek columns during earthquakes with and without Tendon System. Proceedings 3rd International conference on protection of historical constructions (3rd PROHITECH), Lisbon, Portugal