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Evaluation of the Pull Test Method for the Measurement of Static Coefficient of Friction

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Abstract: Measuring static coefficient of friction (SCOF) by pull test, in particular in wet conditions, is considered by many unreliable due to operator errors and sticktion when wet surface is being tested. This paper describes the results of 2880 pull tests that were performed by 12 teams of inexperienced individuals. Each team tested 2 tiles under three conditions: Dry, Wet (tap water) and Soaped water. For each tile, 10 pulls in the 4 cardinal directions (total of 40) were taken. The results indicate that if the tests are executed correctly (according to ASTM C-1028), the SCOF in the wet conditions are well distinguished from the results obtained for dry conditions. Also, as expected, the results for the SCOF for the soaped condition were lower than the ones for the wet conditions. These results might also indicate that there is no need for expensive instrumentation, which cannot be used in some field conditions, for the sole purpose of measuring SCOF.

Keywords: Coefficient of Friction, Slip & Fall, Friction Measurement

1. Introduction

The first Pull Test, for the determination of SCOF, was performed by Leonardo da Vinci at the end of the 15th century [Hutchings (2016)] and over the years it was formulized by Amontons, Coulomb and others [Popova (2015), Tribology History (2020)]. The Pull Test is based on the fundamental understanding of sliding friction. In this case, two rigid objects are in contact with each other and in order to initiate a relative motion between them a force, tangential to the contact surface, has to be applied. This is the friction force that is proportional to the contact force between the surfaces. The Static Coefficient of Friction (SCOF) is defined as the ratio between the friction force and the normal (contact) force.

Based on this fundamental concept, a few portable commercial slip-meters were developed such as: BOT-3000E [BOT3000 (2020)], ASM 825A[ASM (2020)],GS-1[GS-1 (2020)], Heidon H37 3D Muse Tribometer [H37-3D (2020)], Tortus II [TORTUS (2020)] and others. These devices are motorized and electronically controlled which eliminate the need for experienced operators to conduct the test. However, the procedure for a manual Pull Test is simple and easy to perform on site and does not require extensive training.

The procedures to use the above devices (and the manual one) are described in American National Standard Institute (ANSI), American Society of Testing and Materials (ASTM), International Standard Organization (ISO) and others [e.g. ASTM (1996), ANSI (2009)]. One of these standards, ASTM C-1028 [ASTM (1966)], which describes a Pull Test procedure, was withdrawn in February 2014 with the rational “This standard is being withdrawn without replacement due to its limited use by industry”. This test method was criticized, in particular, on two issues i.e. George (2013), Safety Direct America (2020):

1. Repeatability – Since the test is performed manually, the concern is that an operator might introduce errors due to the inability to replicate the test. Or, in case of more than one operator, the results will not be the same due to the way the individual performs the test.
2. Test of wet surfaces – While the test’s procedure is acceptable for dry surfaces, the concern is when a wet surface is being tested the test’s results are affected by a phenomenon called *sticktion*. This will produce higher values of SCOF compared with the ones obtained for the same surface in dry conditions.

Sticktion, as applied to wet testing of walking surfaces, arises as a function of the test slider’s contact time on the surface. If there is any delay between the instant the slip meter pad contacts the surface and the application of the horizontal force (the pulling force), *sticktion* will occur. When a shoe hits a walking surface, the interaction time is very short. On wet surfaces, when the contact time is shorter than 0.2 seconds (200 milliseconds), significant *sticktion* is produced that can result in slip meter readings that are higher under wet conditions than would be obtained on the same surface in a dry state.

Some commercial slip meters such as English XL, BOT-3000, British Pendulum Tester (BPT), Brungraber Mark II and MARK IIIB and others claim to resolve the above issues. These devices require minimum training and the value of the measured SCOF is immediately and explicitly provided to the user. Publication that compared the performance of these devices reported large discrepancies between the SCOF values obtained by the different devices [Jungsoo (2012), Kai (2003), Kai (2009), Gronqvist (1999), Gronqvist (2003), Grieser (2002), Hallas (2006). Chang (2001), Chimich (2020), Powers (1999), Powers (2010), ZURICH (2012), Masory (2016)].

This paper revisits the commonly used pull test and provides the results of a large number of pull tests which give some insight to the issues above.

1. Test Procedure

Forty eight inexperienced individuals, with little background in engineering, were randomly divided into 12 teams of 4 members. Each team tested 2 tiles (see Table 1). Each team was provided with a 3” square 3/8” thick Neolite pad (ASTM D2000 rating AA and 70A shore hardness), a 20(lb) weight and a force gauge (the gauge did not hold the peak reading), bottle of tap water and a bottle of tap water with 0.0625% of commercial detergent.

Six different tiles were used in these experiments: Ceramics, Vinyl, Porcelain with fine sandy texture, Glazed ceramics with grooves, Polished marble and Porcelain with smooth surface.

The instructions provided to the teams were simple:

a. Calibrate the force gage using accurate weights.
b. Measure the weight, used as a load, using an accurate electronic scale.
c. Place the pad on the tile and mount the weight on top of the pad.
d. Pull the assembly parallel to the tile’s surface and measure the force needed to initiate a motion.
e. For the wet and “soaped” surfaces make sure to flood the interface between the pad and the tile and perform the test as soon as possible after the flooding.
f. Repeat the test 10 times in four perpendicular directions of the tile (total 40 reading for each tile).
g. Perform (e) for the conditions: Dry (D), Wet with water (W) and with soaped water (S).

Thus, 160 pull tests were performed on each tile for each of the conditions i.e. Dry (D, Wet with water (W) and wet with soaped water (S). In total 2,880 pull tests were carried out in this experiment.

2. COF Tests Results

The results, using all data, are shown in Figure 1. It shows the average value of the SCOF obtained for each tile (160 readings for each team).

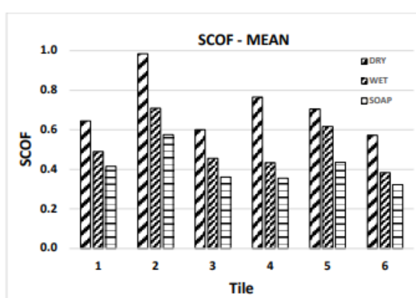


Figure 1: Static Coefficient of Friction (SCOF) mean for the six tiles.

The results obtained for all tiles in the respected conditions are the expected ones which means the SCOF on a water wetted surface is lower than in dry conditions and higher than the one with soap.

However, these results contradict the commonly accepted concern that due to *stickion,* the reading of the SCOF in wet conditions using pull test will be higher than the reading in dry conditions.

The standard error for each of the cases was calculated and is shown in Table 2. As shown the standard error is very small compared to the mean value of the SCOF. Also, for all tests, the largest values of the standard error are in the pull tests under dry conditions. This is due to the fact that the peak value of the pulling force is not recorded automatically by the force gauge and has to be "captured" visually.

Table 1: Standard error for the SCOF of all tiles and test conditions,

Tile	Dry	Wet	Soap	All
1	0.0148	0.0098	0.0102	0.0116
2	0.0211	0.0114	0.0113	0.0146
3	0.0125	0.0069	0.0069	0.0087
4	0.0169	0.0105	0.0088	0.0120
5	0.0121	0.0099	0.0072	0.0097
6	0.0114	0.0113	0.0061	0.00961

Figure 2 shows the results obtained for each tile and by each team; Table 2 provides the corresponding standard error for each case. From Figure 2 and the values in Table 2, it can be concluded:

a. As expected, the SCOF of the dry tiles is higher than the one of the wet ones, except for one case.
b. As expected, the SCOF of the water wetted tiles is higher than the one wetted with soaped water.
c. In some cases, there are large differences between the SCOF's values obtained by different teams. For example, Tile 1 Team 5T obtained SCOF=0.96 while Team 3T obtained the value of 0.57.
d. The standard error for all cases, shown in Table 2, is one order of magnitude lower than the nominal value of the SCOF.

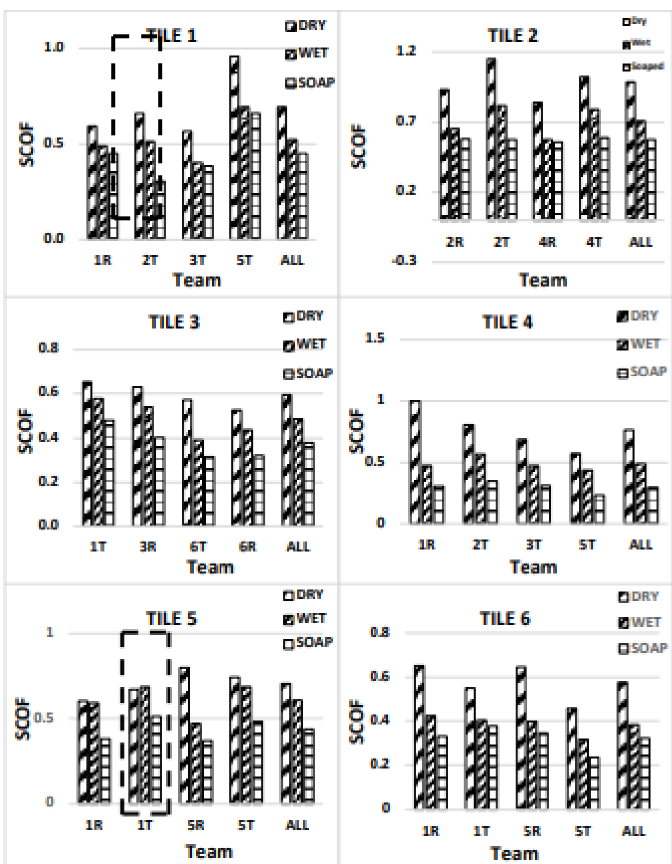


Figure 2: Tests results for all tiles.

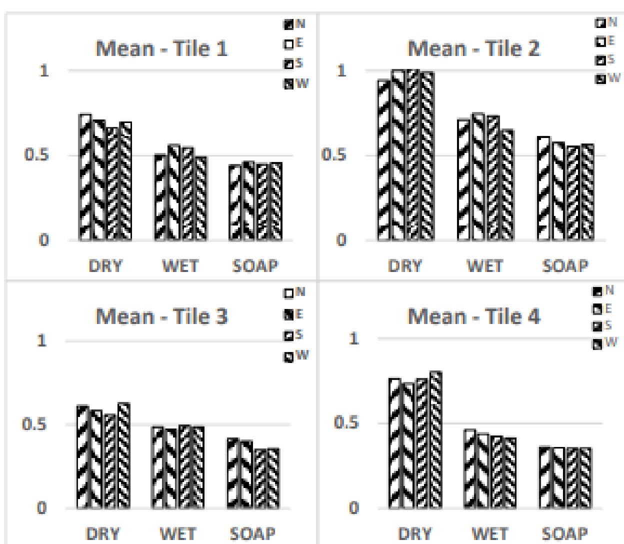
Table 2: Standard error for each test shown in Figures 3.

TILE	TEAM	STANDARD ERROR			TILE	TEAM	STANDARD ERROR		
		DRY	WET	SOAP			DRY	WET	SOAP
1	1R	0.022	0.015	0.027	4	2R	0.022	0.010	0.017
	2T	0.024	0.023	0.013		4R	0.036	0.016	0.017
	3T	0.022	0.025	0.016		6R	0.023	0.023	0.017
	5T	0.041	0.012	0.020		6T	0.053	0.034	0.017
2	2R	0.040	0.013	0.013	5	1R	0.020	0.018	0.016
	2T	0.036	0.018	0.019		1T	0.015	0.013	0.016
	4R	0.037	0.019	0.025		5R	0.032	0.018	0.016
	4T	0.055	0.040	0.033		5T	0.030	0.029	0.016
3	1T	0.016	0.008	0.018	6	3R	0.018	0.016	0.015
	3R	0.018	0.016	0.010		3T	0.026	0.017	0.015
	6R	0.016	0.011	0.016		4T	0.031	0.018	0.015
	6T	0.053	0.014	0.019		5R	0.016	0.022	0.015

3. Effect Of Pulling Direction

The manufacturing process of some tiles is directional, e.g. extruded ceramics tiles, while in others, such as polished marble tile, it is not. To find whether or not the SCOF value is influenced by the manufacturing process, t-Test was performed for all pairs of pulling directions combinations: NE, NS, NW, ES, EW and SW. The test answers the question if the means of SCOF of the pair are the same or not ($P<0.05$). Table 3 summarized the results obtained by the t-Test: S means that statistically the pair have the same mean and D means that statistically that the means are different.

Although the results of the t-Test indicate that the pulling direction does affect the value of the SCOF in some cases, at least from statistical point of view, one has to realize that practically the differences are small and irrelevant when the SCOF is measured on actual sites where the conditions to perform the test are not ideal. Figure 3 shows the mean values of the SCOF for the four perpendicular directions of the pulls. As can be seen the differences are very small and considering the errors in the testing procedure, the errors are not significant.



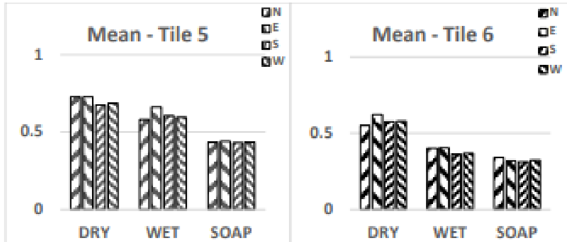


Figure 3: SCOF for all tiles at different pulling directions.

4. Teams' Performance

The performance of each team can be measured by the standard errors of their results. Thus, the results given in Table 2 were rearranged and plotted in Figure 4a. A small value for the standard error indicates more attention and strict following of instructions (see framed cases in Figure 4a teams 3R, 6R and 1T). On the other hand, a large value of the standard error indicates poor attention to the testing procedure (see Figure 4b teams 4T and 6T).

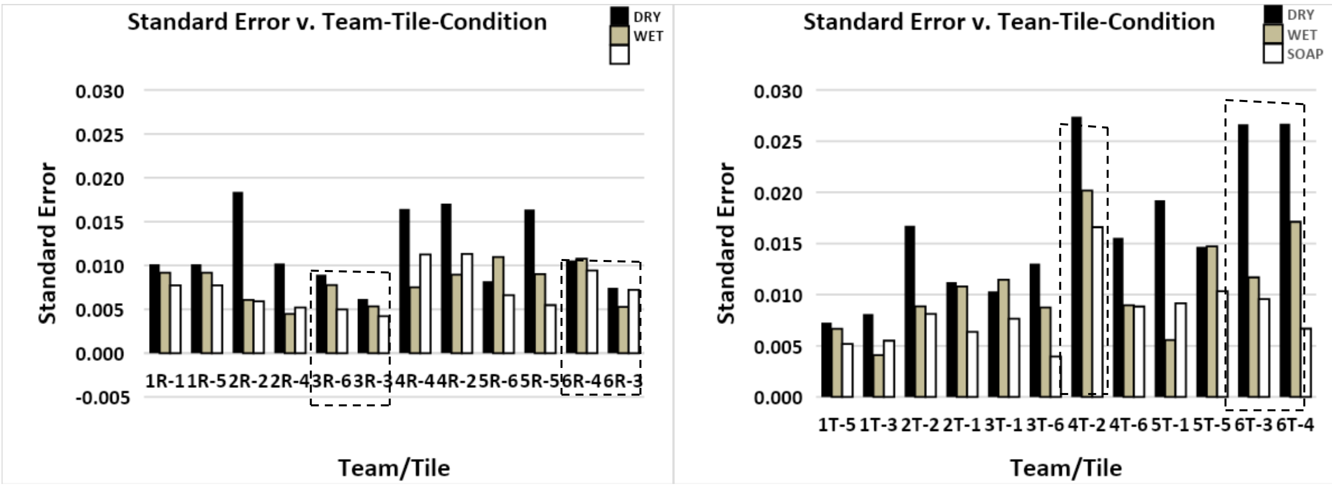
5. Conclusions

The results of a large number of pull tests that were performed by inexperienced operators on 6 different tiles in three different surface conditions have been presented. The results lead to some conclusions:

a. The pull test is valid for wet surfaces when it is performed correctly.
b. Training will improve the results.
c. The use of the right force gauge, which records the peak value of the pulling force, will improve the results.
d. The number of tests cannot be fixed and should increase to the point where the standard error reaches a certain value (e.g. 5%).
e. The test does not require expensive equipment.

Table 3: t-Test results.

TILE	CONDITION	DIRECTIONS					
		NE	NS	NE	ES	EW	WS
	DRY	S	S	S	S	S	S
1	WET	S	S	S	S	**D**	**D**
	SOAP	S	S	S	S	S	S
	DRY	S	S	S	S	S	S
2	WET	S	S	**D**	S	**D**	**D**
	SOAP	S	**D**	**D**	S	S	S
	DRY	S	**D**	S	S	S	**D**
3	WET	S	S	S	S	S	S
	SOAP	S	**D**	**D**	**D**	**D**	S
	DRY	S	S	S	S	S	S
4	WET	S	**D**	**D**	S	S	S
	SOAP	S	S	S	S	S	S
	DRY	S	**D**	S	**D**	S	S
5	WET	**D**	S	S	S	S	S
	SOAP	S	S	S	S	S	S
	DRY	**D**	S	S	**D**	**D**	S
6	WET	S	**D**	**D**	**D**	**D**	S
	SOAP	**D**	S	S	S	S	S



(a) (b)

Figure 4: Team performance as indicated by the standard error.

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