Suspension Effect in Rotating Surface Erosion Testing

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ABSTRACT

Surface erosion is a scouring process on the exterior surface of soil, which is recognized as one of the major threats to the waterborne infrastructures. Soil grains are removed by flowing fluids during the erosion process, which can be suspended in the eroding fluid. However, the suspension effect has not been addressed in most existing erosion testing devices. The suspension effect on soil erosion mainly includes the fluid property change (i.e., viscosity) and the interaction between the fluid with suspended particles and the specimen surface. In this research, the suspension effect was evaluated in a newly developed Rotating Surface Erosion Apparatus (RSEA) using a dummy specimen with prescribed surface roughness. Variations of the hydraulic force with the fluid viscosity were determined for different types and concentrations of suspension. Based on the results, a calibration chart for suspension effect was established to improve the accuracy of soil erosion testing.

1. INTRODUCTION

Surface erosion is a scouring process on the exterior surface of soil, in which soil grains are removed by flowing fluids. Surface erosion is one of the major threats to the waterborne infrastructures. It was reported that more than 60% of bridge failures was caused by erosion, which was 30 times of those caused by earthquakes (Shirole and Holt 1991). Moreover, surface erosion also caused more than 30% of dam failures (Costa et al. 1985). Overtopping led to the breaching of levees and caused severe flood events downstream.

To investigate the erosion behavior of soils, many types of erosion apparatuses have been developed. For example, straight flumes have been widely used for examining the soil erodibility (Kandiah and Arulanladan, 1974; Shan et al., 2015). The flume was connected to a pump and reservoirs to generate open channel flow for erosion testing. Scouring around bridge piers was also simulated in flumes with a block ratio (blocked width/flume width) smaller than 12% (Tao et al., 2018; Amini et al., 2012). Closed conduits such as SEDFlume (sediment erosion at depth flume) and EFA (erosion function apparatus) were also used to evaluate soil erodibility, which generated a high-speed pipe flow inside a closed channel (McNeil et al.,1996; Briaud et al., 2001). Furthermore, rotational erosion devices were also used by many researchers for erosion analysis (Moore and Masch, 1962; Chapuis and Gatien, 1985; Lin and Lin, 2023). The cylindrical chamber was spun by a motor to create Taylor Couette flow for eroding a cylindrical soil specimen.

Currently, the excess shear stress equation, $\dot{\varepsilon} = K_d(\tau - \tau_c)$, is widely accepted for erosion analyses (Briaud et al. 2001). Soil erosion rate ($\dot{\varepsilon}$) was examined at different hydraulic shear stresses (τ). However, during an erosion test, soil grains removed by eroding fluid can be suspended, which changes the fluid viscosity. Vladimir (1948) examined the viscosity of fluid with suspended spherical particles. The results showed that 5% and 10% concentrations of suspension increased the viscosity by 14.5% and 34.2% respectively. Konijin et al. (2014) examined the viscosity of nearly neutrally buoyant suspensions. They concluded that the relative viscosity, i.e., the ratio between suspension and liquid viscosities, is a rapidly increasing function of solid fraction. As soil becomes suspended in fluid, erosion testing is affected by the suspension via higher shear stress and redeposition of soils. Xiao (2018) examined the effects of fluid properties on the movement of a single sphere. The results indicated that the viscosity has the most influence on the incipient motion of a granular particle. Brandimarte et al. (2012) revealed that the development of scour around the bridge is also related to the suspension. In clear water (no suspension), the scour depth increases slowly to a plateau. However, in the live bed conditions with soil from upstream suspended in fluid, the scour depth increases rapidly and then fluctuates around the equilibrium depth, balancing the erosion and redeposition of soil.

Thus, the suspension of eroded soil grains is critical, especially for the erosion tests in a circulating system, in which the eroded soil is not collected and keep influencing the tests. However, the effect of suspension was rarely addressed in the developed erosion apparatuses. This paper examines the effect of suspension on erosion testing in a newly developed rotational erosion apparatus, i.e., RSEA. Variations of the hydraulic shear stress with different types and concentrations of suspension were determined at various rotational speed. Based on the results, a calibration chart was established for considering the suspension effect at a given suspension concentration and chamber speed.

2. METHOD OF EXPERIMENT

2.1. Rotating surface erosion apparatus

A customized rotating surface erosion apparatus (RSEA) was used in this research to evaluate the effect of suspension in eroding fluids. Figure 1 shows the assembled RSEA, which mainly includes a compact motor, a DC power supply, a transparent rotating chamber, a specimen set, a tachometer, a data logger, and a torque measurement assembly. The specimen set is composed of a specimen and two plastic caps, which stay stationary during the test. The outer chamber is driven by the compact motor through a belt transmission system. The rotation speed (RPM) is controlled by changing the input DC voltage using the power supply and is measured by the tachometer. As the chamber rotates, the fluid in the chamber is accelerated and induces hydraulic shear stress to the surface of the specimen-set. The hydraulic force is balanced and measured from the torque measurement assembly mounted on the top of the apparatus, as shown in Figure 1. The rate of erosion is obtained by collecting the eroded soil particles from the chamber after a certain time of testing. Greater details of the RSEA can be found in Lin and Lin (2023).

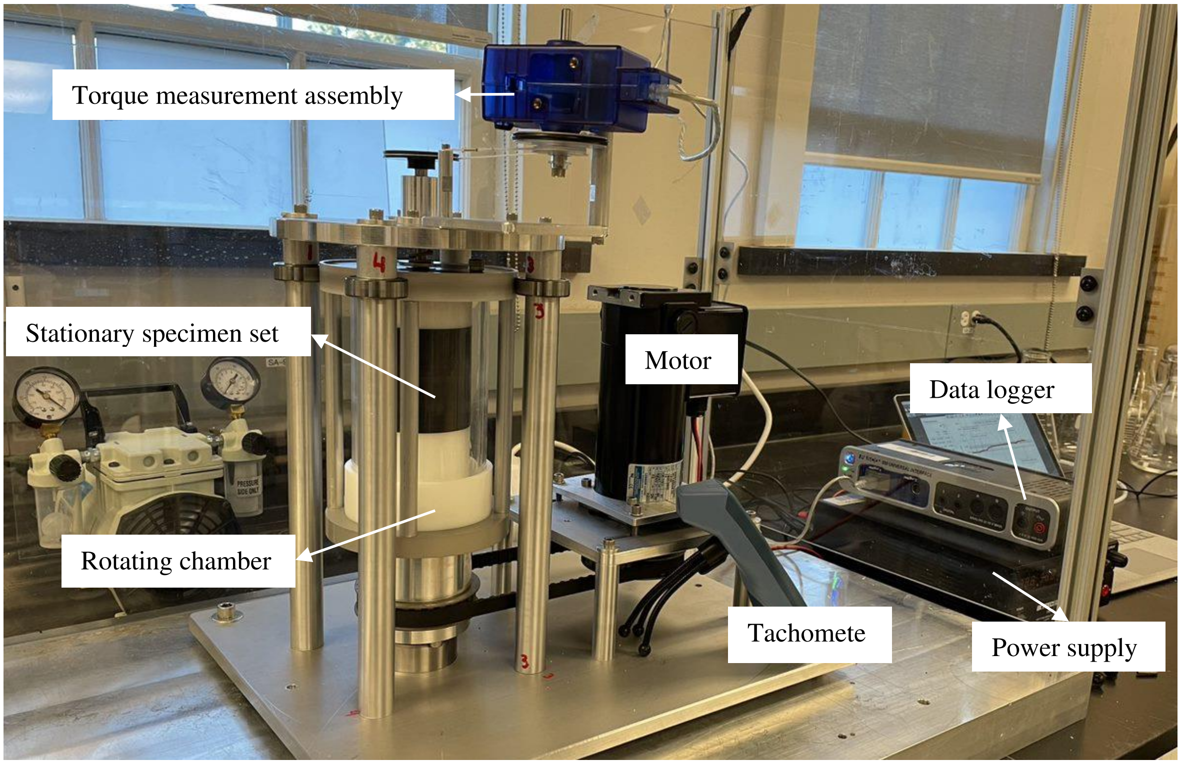

Figure 1. Rotating surface erosion apparatus

2.2. Materials

To evaluate the suspension effect in the soil erosion tests, dummy specimen-set were used in this research. Soil in the suspension was made of a mixture of clay and sand. Clay was Tile #6 Kaolin with 0.5% of the particles greater than 45 μm and 60% finer than 2 μm. The components of the Kaolin are listed in Table 1. Sand was poorly graded sand passing No. 20 U.S. sieve (0.84 mm). Its grain size distribution is shown in Figure 2. The surface of the specimen-set was covered by sandpaper to simulate the rough soil surface, as shown in Figure 3(a).

Table 1. Chemical composition of Kaolin

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	CaO	MgO	L.O.I
45.5%	38.1%	0.5%	1.4%	0.1%	0.3%	0.4%	13.5%

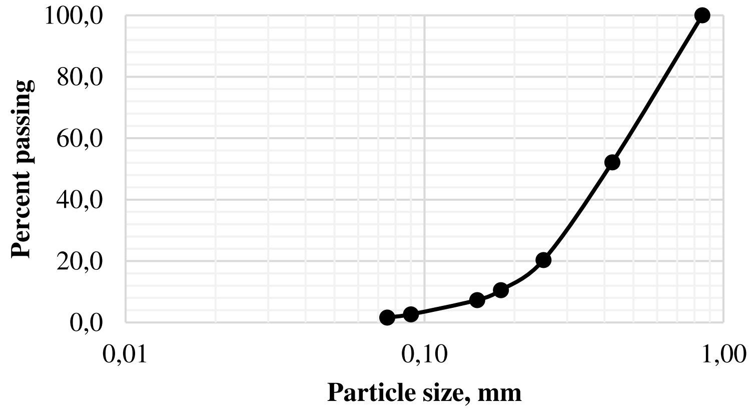

Figure 2. Grain size distribution

Soil in the suspension contained three clay-sand mixing ratios: i.e., K100S0, K70S30 and K30S70 in which K and S represent kaolin and sand, respectively, and the numbers represent the weight percentage of each soil. The suspension was prepared by mixing the soil with distilled water at various concentrations (0%, 1%, 3%, and 5%). The numbers cover a typical range of suspension concentrations generated during erosion testing using RSEA. Suspension effects were then evaluated at different chamber rotation speeds (RPM: 250 – 1400). Prior to the test, the suspensions were sufficiently stirred using a magnetic stirrer to ensure uniformity, as shown in Figure 3(b). The suspensions were then used as eroding fluids in RSEA.

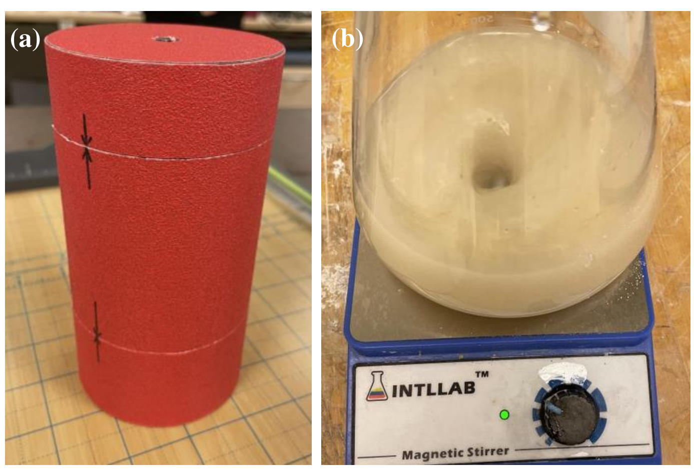

Figure 3. Prepared specimen-set and suspension

3. RESULTS AND DISCUSSION

As the soil became suspended in the eroding fluid, the viscosity increased, which led to a higher torque measurement from the specimen-set and a higher hydraulic shear stress on the specimen surface. Figure 4 presents the measured torque from the assembly (Figure 1), using the eroding fluid with different concentration of K70S30. It can be seen that the RSEA could capture the effects due to changes in suspension in the eroding fluids. As the concentration of suspension increased, the torque for balancing the hydraulic shear force increased correspondingly. In other words, the suspended soil particles impose additional shear stress to the cylindrical specimen surface, as shown in Figure 3(a). Thus, at a given hydraulic condition (i.e., RPM), the suspension induced changes in erosive force should considered in soil erosion testing.

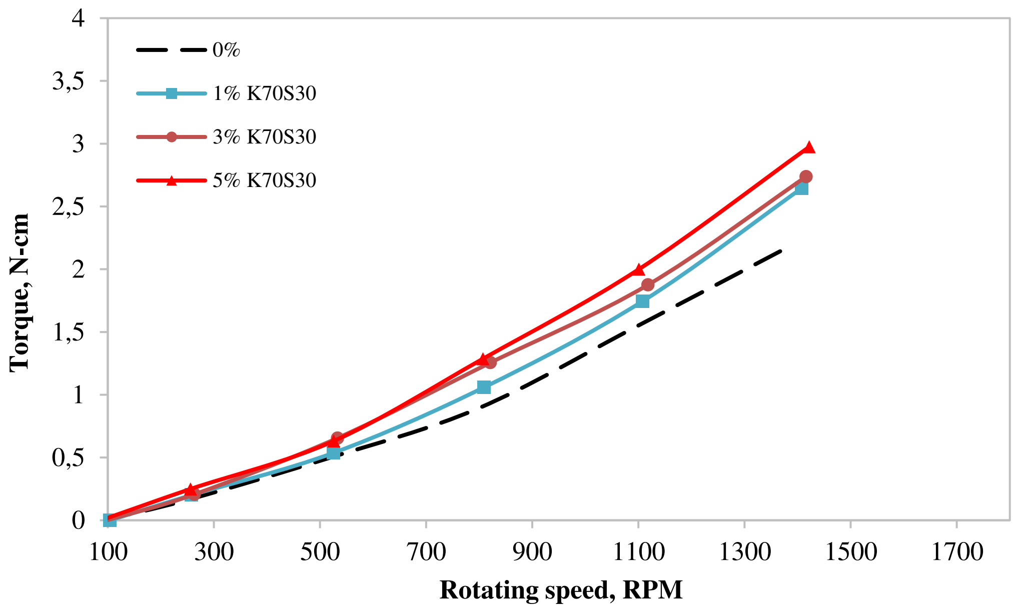

Figure 4. Measured torque at various RPMs for K30S70

In this research, suspension effect on the induced shear stress on the dummy specimen surface was evaluated. Three typical variants on erosion tests using RSEA were evaluated to address the suspension effect: a) RPM, b) concentration of suspension, and c) soil types in suspension. To quantify the suspension effect, the ratio of measured torque-i.e., the measured torque with suspension divided by that without suspension is introduced. The higher this ratio, the greater influence that the suspension has on erosion test results.

3.1. Effect of rotating speed

Figure 5 presents the ratio of measured torque at different rotating speed (RPM) for different suspension concentrations. The presence of suspended soil in eroding fluids resulted in an increase in the measured torque by 24%-68%, with the most notable increase occurring at low RPM. As the rotating speed increased, the ratio of measured torque decreased rapidly and tended to stabilize. In other words, the suspension effect became less significant at higher RPMs (i.e., >500 RPM). The reason is that the spinning-induced centrifugal force moved the suspended particles outwards, resulting in fewer particles at the soil-fluid interface and more particles at the fluid-chamber wall interface. For 5% suspension concentration, the ratio of measured torque decreased by 0.33 as the chamber speed increased from 259 to 528 RPM, while the total reduction was only 0.37. Thus, it can be concluded that the suspension effect was more crucial at lower RPMs and became relatively stable and less significant after 500 RPM.

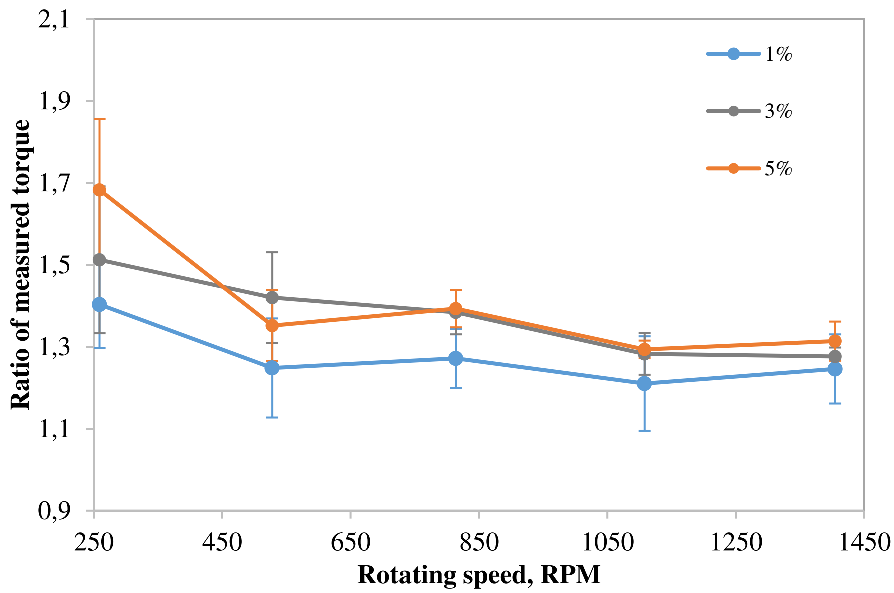

Figure 5. Suspension effect at different RPMs

Figure 6 shows the accumulated soil on the rotating chamber after the test, which confirmed that the previous discussion that fewer particles remained at the soil-fluid interface and the suspension effect was less noticeable at larger rotating speeds. The above result indicates that RSEA enjoyed an advantage over other erosion testing devices as its generated centrifuge forces could mitigate the suspension effect (or fluid viscosity) on the erosional results. Moreover, redeposition of eroded soil particles was also depressed in RSEA. This is another favorable feature as the eroded particles tend to enhance the adhesion between aggregates, hence, decreasing the erodibility of the soil samples (Larionov et al 2008).

Figure 6. Accumulated soil on the chamber

3.2. Effect of suspension concentration

Figure 7 indicates the suspension effect at different suspension concentrations. In general the concentration impact on the measured hydraulic shear was less significant than RPM in Figure 6. It is clearly shown that a higher concentration of suspension led to a larger ratio of measured torque. Thus, for a typical erosion test, the suspension effect can be increasingly notable as more soil particles detach from the specimen surface and become suspended in the eroding fluid. Figure 7 also shows that influence of concentration of suspension was more significant at low rotating speed. As the concentration increased from 1 to 3%, the ratio of measured torque increased by 0.28 at 259 RPM, while the increment was only 0.07 at 1405 RPM.

x

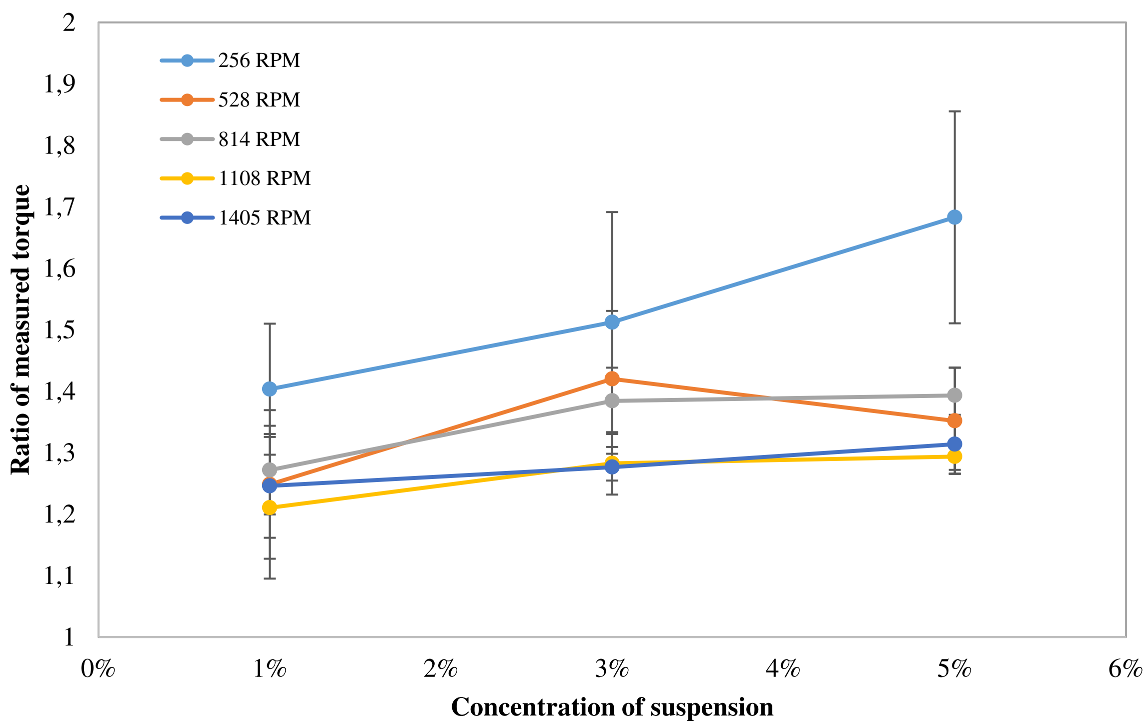

Figure 7. Suspension effect at different concentrations

3.3. Effect of soil types in suspension

Three types of soils were examined in this research, which are referred as K100S0, K70S30 and K30S70 as mentioned above. Figure 8 presents the suspension effects of different testing soil types at different RPMs. In general, the ratio of measured torque decreased with the increasing rotating speed, which is consistent with the previous findings. In other words, the suspension effects became less significant in a higher RPM in rotational device, regardless of what soil was suspended in the eroding fluids. As the rotating speed increased from 259 to 1405 RPM, the K100S0 exhibited greatest reduction of the ratio of measured torque. Thus, the suspension effect is possibly related to the clay concentration as fine particles like Kaolin was much easier to be suspended in the eroding fluid while heavier sand particles tended to settle. However, the increase in sand content in the soil did not necessarily reduce the suspension effect herein. This is likely that for narrowly gapped rotational erosion device, the sand particles could be accumulated in the bottom of the chamber which might affect the measurement from the lower specimen plate. More research is needed to investigate the suspension effect of different clay minerals (e.g., kaolin vs. bentonite) on surface erosion testing.

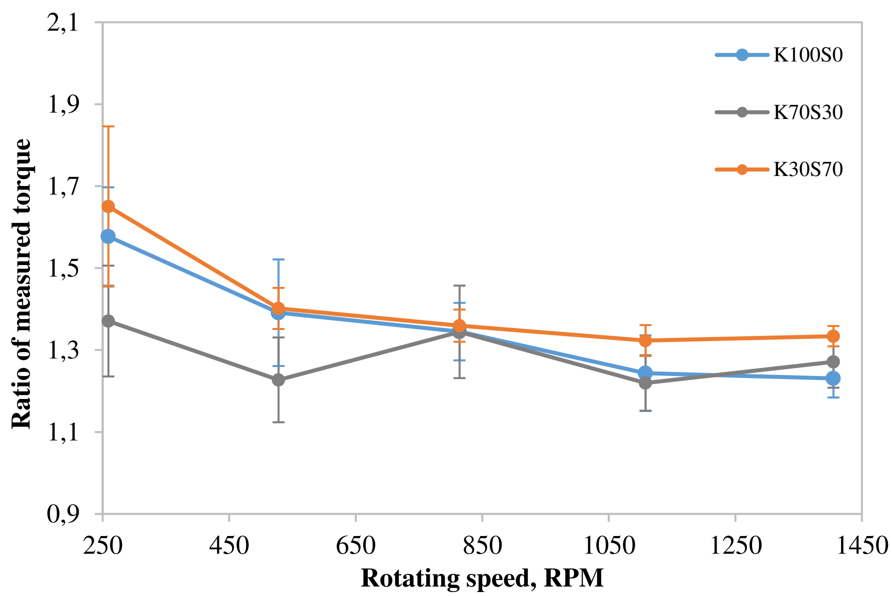

Figure 8. Suspension effect of different soil types

Figure 9 presents the contour of typical values of the ratio for different concentrations of suspension at various hydraulic conditions. The soil type effect was averaged out, so that the figure can be used as a general reference for predicting the suspension effect in RSEA. As shown in Figure 9, the suspension effect led to an increment of hydraulic force by up to 60%. As the chamber rotating speed increases and the suspension concentration decreases, a lower ratio of measured torque can be predicted-in other words, the suspension effect is anticipated. For a normal suspension concentration (1%) in erosion testing using RSEA, the torque measurement can be typically increased by 20 – 40% as compared with the erosion tests using pure water.

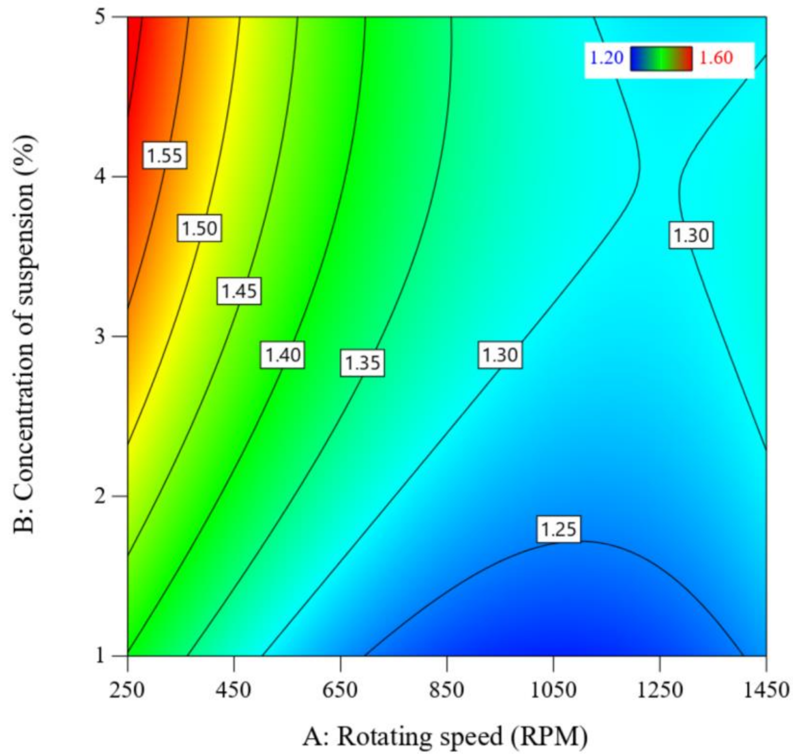

Figure 9. Typical range of suspension effect

4. CONCLUSIONS

This paper presents the suspension effect in the recently developed rotating surface erosion apparatus (RSEA). The suspension was made of distilled water and soil. Three different types of soils (K100S0, K70S30 and K30S70) with various suspension concentrations (0%, 1%, 3%, and 5%) were examined at various hydraulic conditions. The results indicated that the hydraulic erosion force could be increased by up to 68% due to the increased viscosity of eroding fluid with suspended soils. The suspension effect was less notable at lower concentrations. For 1% suspension, the ratio of measured torque ranged from 1.2 to 1.4. Furthermore, the suspension effect was more pronounced at lower RPMs. As the chamber rotating speed increased, the suspension effect became less significant in RSEA and was relatively stable after 500 RPM due to the centrifuge field developed during the rotation, which tended to move eroded soils to the outer chamber. This is an important favorable feature of RSEA. Lastly, a contour was generated for predicting the suspension effect at a given concentration and chamber speed. For a typical test in RSEA, the increase in erodibility due to suspension effect (due to low plasticity clay) might be taken as 20%-40%. Note that the suspension effect via redeposition of fines was not considered in this research, as it was insignificant due to the centrifugal field in the rotational device. Further research is necessary on the suspension comprised of high plasticity clay.

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