PLOUGHING OF WORK-HARDENING ASPERITIES BY A HEMISPHERICAL SLIDER

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ABSTRACT

A theoretical description is given for the ploughing of a work-hardening inclined surface by a hemispherical slider. As the indenture is moving horizontally, the grooving force and the depth of penetration are expressed for conditions that correspond to the climbing and descending asperities. Assuming a constant vertical load on the slider, the friction coefficient due to ploughing, F_P, is shown to be affected by surface inclination moreover, the limiting value of F_P when the vertical load on slider is made infinitely small is shown to be independent upon the asperity angle and the shape of the slider. The treatment has some use in predicting the extent of surface damage in contact profilometry, especially for soft materials in particular, the depth of penetration is shown to be different when climbing or descending a surface whose inclination is θ.

الخلاصه:

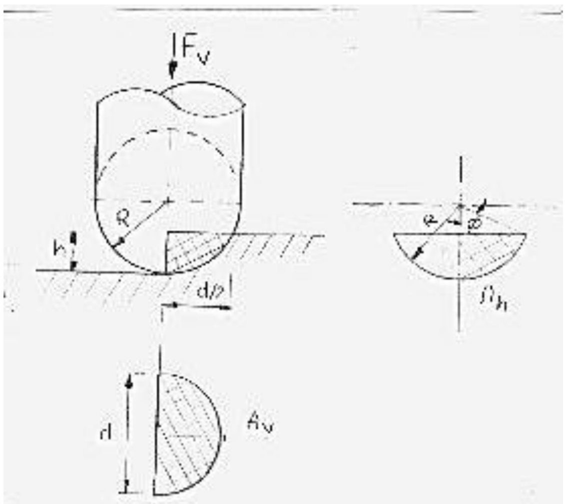
تم اجراء توصيف نظري لعملية حرث سطح مائل مصلدبالتشغيل بواسطة منزلق نصف كروي . عندما يتحرك المنزلق الخارق أفقياً، فأن قوى الحرث وكذلك عمق الخرق تم التعبير عنها لحالة التسلق والآنحدار للنتؤ.
بأفتراض وجود حمل عمودي ثابت على المنزلق فأن معامل الأحتكاك نتيجة الحرث F_p تبين بأنه يتأثر بميلان السطح بألآضافه الى أنه القيم الحديه ل F_p عندما الحمل العمودي على المنزلق يصل الى قيم متناهيه في الصغر أثبت أنه يعتمد على زاوية النتؤ وشكل المنزلق.
هذه المعالجه لها بعض الأستخدامات في التنبؤ بمدى تشوه السطح في تلامس البروفايلوميتر (profilometry) خاصه للمعادن اللينه.

على وجه الخصوص، عمق الخرق أثبت أنه يختلف عند التسلق أو الأنحدار من سطح ميلانه θ .

INTRODUCTION:

When a rigid indenter slides over a work-hardening surface, the resistance to motion is generally due to two different factors: the elastoplastic deformation of metal, or ploughing, and the adhesion at the interface of the components. This physical phenomenon is treated in text books on tribology [Moore. D.F. 1975] and a number of experiments which have been performed to establish the validity of some mathematical models or to analyze the wear mechanism in this study, an extension to classical demonstration about the ploughing component of friction are presented. One of the aims to model how surface damage is done in contact profilometry when a slider or a tiny rigid stylus travels on a surface showing an irregular profile for the proposed mathematical models, the shape of asperities is simplified as to be represented by straight inclined surface . Therefore, relative to the primary direction of motion, the slider has to climb or descend surfaces inclined at an angle θ , as shown in fig. (1). Note that in this work, and contrary to the usual terminology, the word `asperity` is associated with the surface that is being deformed and not with the slider.

Fig.(1) Representation of a Slider Moving on Horizontal, then Inclined Surface .



Fig(2) Hemispherical Slider Moving on Horizontal surface

PLOUGHING OF A HORIZONTAL SURFACE:

The ploughing component of friction is often modeled assuming that a slider of simple geometry moves parallel to an ideally flat surface and grooves its path into it. Fig.(2) represent such situation with a hemispherical slider of radius R deforming plastically a softer, yielding material in the following development the following assumption are made.

- Material pile-up surrounding the slider is neglected.
- Effects of slider speed (inertial forces) and heat generation (modification of material properties) are not considered.

A static analysis of force balance gives a relation ship between the vertical load , F_V, and the extent of surface damage in terms of groove width, d, or groove depth, h, and yield pressure P_y, as in fig.(2) .

$$F_V = P_Y \times A_V = P_Y(\pi d^2/8) = P_Y \lambda \pi R h/2$$

From [J.Halling 1975] Halling found λ to be

$$\lambda = 2 - n^{0.5}$$

$$F_V = \frac{1}{2} P_y (2 - n^{0.5}) \pi R h$$

$$h = R - (R^2 - (d/2)^2)^{0.5}$$

$$F_V = P_y(\pi/2)(2-n^{0.5})R^2(1-(1-(d/2R)^2)^{0.5})$$ --(1)

The horizontal force opposing motion is derived similarly and yields

$$F_h = P_y A h \lambda/2 = P_y \lambda R^2(\Phi - d/2R(1-(d/2R)^2)^{0.5})/2$$

Where $\Phi = \sin^{-1}(d/2R)$; $\lambda = 2 - n^{0.5}$

n: work hardening index (0) for plastic (1) for elastic

$$F_h = P_y(2-n^{0.5})R^2/2(\sin^{-1}(d/2R) - d/2R(1-(d/2R)^2)^{0.5})$$ ----------------------------(2)

We can now write the expression for the coefficient of friction due to ploughing. It is the ratio of the horizontal and vertical forces:

$$F_P = F_h / F_V = A_h / A_V$$ ---(3)

Eqs.(1and2) are given independently as a function of d,h,n and R since those parameters are of more practical importance than Φ. The width can be estimated by observing a grooved surface under the microscope. The depth of penetration may be useful in interpreting data related to surface profilometry.

In the same way , other basic slider shapes have been investigated, namely the cylinder, cone and pyramid[Nam P. 1970, Hisakado T. 1970 , Sin H.G.1979].

PLOUGHING WHILE CLIMBING OR DESCENDING AT θ:

We now consider a hemispherical slider that climbs fig.(3) or descends fig.(4) a surface having an inclination θ.

The load on the slider, F_V, is assumed to be remain constant and vertical Eq.(1) still applied and , in non dimensional terms we define .

$$F_V{}^* = \frac{F_V}{P_Y(\pi R^2/2)} = \frac{A_V}{\pi R^2/2} \quad \text{------(4)}$$

In the present analysis the contact is restricted to the lower hemisphere that is for

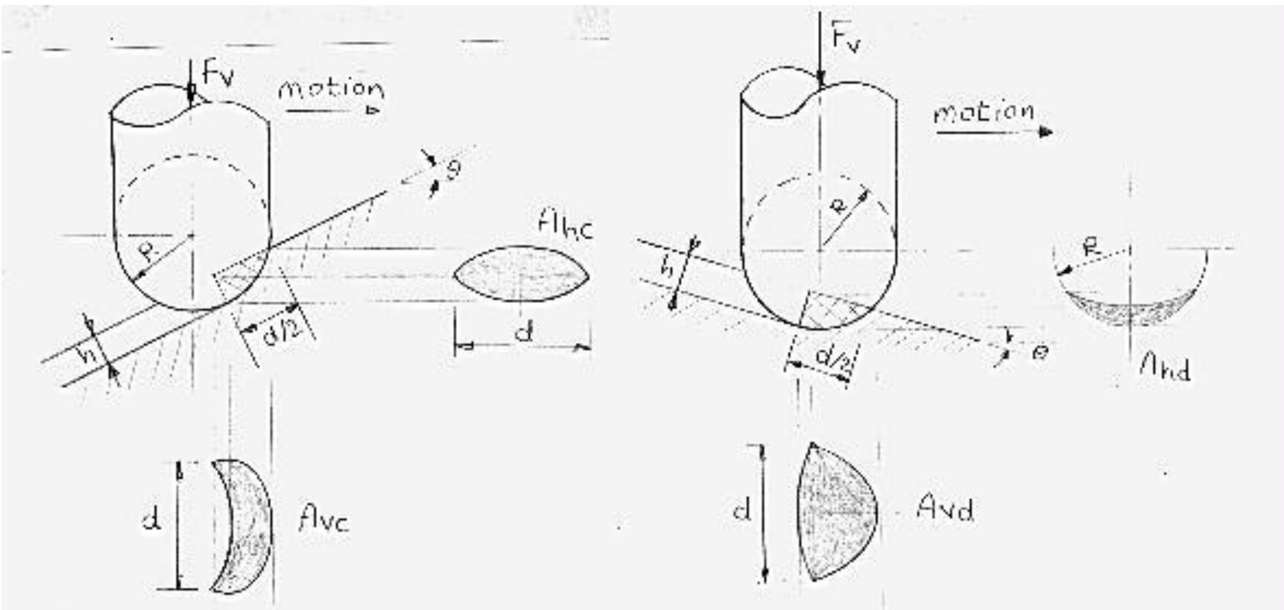
$$\theta \le \cos^{-1}(d/2R) = \theta_{max} \quad \text{------(5)}$$

WIDTH OF GROOVING:

The projected areas A_{vc} and A_{vd} (fig.3 and fig.4) are composed of elliptical and circular segments subtracting or adding with each other. With proper geometrical considerations, one obtain the following equations

$$F_V{}^* = \frac{A_{VC}}{\pi R^2/2} = \frac{(\pi/2)(2-n^{0.5})R^2\{1-(1-(d/2R)^2)^{0.5}\}\cos\theta}{\pi R^2/2} - \frac{0.5(2-n^{0.5})R^2\{\sin^{-1}(d/2R)-(d/2R)(1-(d/2R)^2)^{0.5}\}\sin\theta}{\pi R^2/2}$$

$$F_V{}^* = (2-n^{0.5})\{1-(1-(d/2R)^2)^{0.5}\}\cos\theta - \frac{(2-n^{0.5})}{\pi}\{\sin^{-1}(d/2R) - (d/2R)(1-(d/2R)^2)^{0.5}\}\sin\theta \quad \text{------(6)}$$



Fig(3) Hemispherical Slider Climbing an Inclined Surface at θ

Fig.(4) Hemispherical Slider Descending an Inclined Surface at θ

$$F_V^{\ *} = \frac{A_{Vd}}{\pi R^2/2} = (2-n^{0.5})\{1-(1-(d/2R)^2)^{0.5}\}\cos\theta + \frac{(2-n^{0.5})}{\pi}\{\sin^{-1}(d/2R) - (d/2R)(1-(d/2R)^2)^{0.5}\}\sin\theta \quad \text{----------(7)}$$

By substituting eq.(4) into eq.(6) and eq(7) it is possible to calculate the width of the grooving at various angles and work-hardening index for any test parameter values.

Results are given in fig.s(5.1,2,3,4) for a climbing trajectory and in fig.s(6.1,2,3,4) for a decent. To maintain vertical force equilibrium (for given values of R and P_Y), the groove width has to increase in a non-linear fashion with increasing θ and with the increasing of the work-hardening index n.

By comparing the graphs one can see that for a given F_V^* the width of grooving is always when descending than climbing at the same θ and n (i.e. $A_{Vd} > A_{VC}$). The difference also becomes larger as the angle gets steeper. Mathematically, this is explained by the facts that the second right-hand term of eq.(6) and eq.(7) is always small in comparison with the other.

Figures 5 and 6 could be used to predict the groove width when a stylus is used for surface measurements of hard and soft surfaces. By knowing the geometry of the stylus, the depth of indentation could also be determined.

FRICTION COEFFICIENT:

The friction coefficient due to ploughing is calculated using generalized form of eq(3) as the ratio of the horizontal and the vertical projected areas.

For climbing an asperity, and referring again to fig.(3) the horizontal projected areas is:

$$\frac{A_{hC}}{\pi R^2/2} = (2-n^{0.5})\{1-(1-(d/2R)^2)^{0.5}\}\sin\theta + \frac{(2-n^{0.5})}{\pi}\{\sin^{-1}(d/2R)-(d/2R)(1-(d/2R)^2)\}\cos\theta \quad \text{-----------(8)}$$

One can now obtain the analytical expression for the friction coefficient F_p by dividing eq.(6). The result is shown graphically in fig.s(7.1,2,3,4) as a function of the non dimensional load F_V^* while F_p never exceeds 1.0 in the more conventional case of ploughing a horizontal surface, it may theoretically increases in sever climbing conditions.

For descending an asperity, and referring to fig.4 the horizontal projected areas is:

$$\frac{A_{hd}}{\pi R^2/2} = \frac{(2-n^{0.5})/2}{\pi R^2/2}\{R^2\phi - \frac{R\sin 2\phi}{2} - \frac{R^2\pi}{2}[(d/2R)-\tan\theta(1-(d/2R)^2)^{0.5}]\sin\theta\sin\phi\}$$

$$= \frac{2-n^{0.5}}{2}\{2\phi/\pi - \sin 2\phi/\pi - \frac{d\sin\theta\sin\phi}{2R} + (1-(d/2R)^2)^{0.5}\tan\theta\sin\theta\sin\phi\} \quad \text{-----(9)}$$

Where $\phi = \cos^{-1} \frac{(1-(d/2R))^{0.5}}{\cos\theta}$

In this analysis the specific angle at which no resistance to motion occurs when descending an asperity can be expressed mathematically by:

$$\theta = \tan^{-1} \frac{(d/2R)}{(1-(d/2R)^2)^{0.5}} = \sin^{-1}(d/2R)$$

The friction coefficient that applies in a descend is obtained by dividing eq(9)by eq(7) and a graphical representation of it appears in fig.s(8.1,2,3,4) as a function of the non dimensional load F_V^*.

Figs.7 and 8 show that the friction coefficient due to ploughing increases and the slope of the asperity increases during climbing the asperity, on the contrary decreases when the slider descends [Ishizuka 1985] has found that the friction coefficient between a hard conical projection and soft rubbing surface having the projection of triangular prism increases with increasing the half angle of the prism which is well represented by the present model for descending a surface whose inclination is θ.

CONCLUSIONS:

Essentially the extent of ploughing can be the depth of penetration of a soft material by a hard slider. This factor is a function of the shape and size of the indenter, the load applied on it, the work-hardening index and the yield pressure of the material that under goes grooving.

Taking into account only ploughing component of friction, it was demonstrated that a simple model can be extended to predict damage on rough surfaces.

In the case of a hemispherical slider climbing and descending asperities that are represented by inclined surfaces, the groove width was shown to be dependent upon the inclination θ.

REFERENCES:

* Hisakado T. "On the mechanism of contact between solid surfaces " Bull. of the JSME,13,1970.

* Ishizuka S. "Fundamental studies on dry friction" proc. of the JSLE, Int Tribology conf. 1985, p135-139

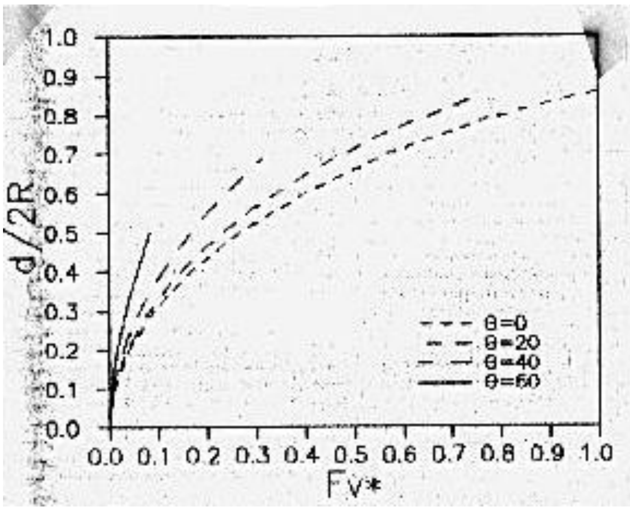
* J.Halling and K.A.Nuri "Contact of rough surfaces of work hardening materials " Proceedings of the symposium of the international union of theoretical and applied mechanics. 1975

* Moore D.F. "Principles and applications of tribology" 1975.

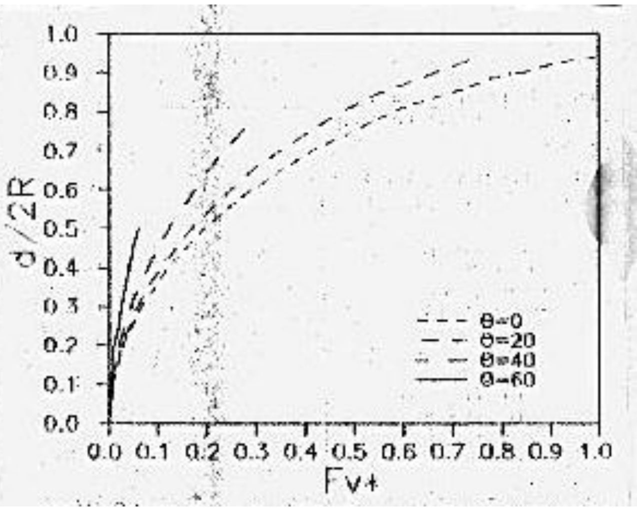
* Nam P. Suh." Elements of the mechanical behavior of solids."

* Sin H.C. , Saka N. and Suh H.P. "abrasive wear mechanisms and the grit size effect" Wear ,55,1979

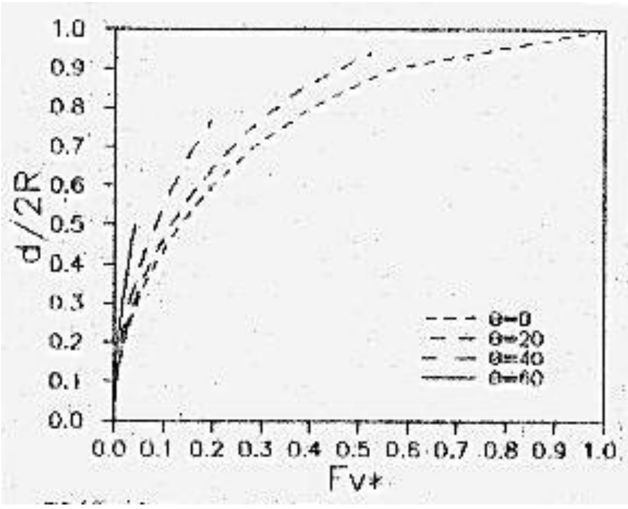
* S.M.H. Benabdallah and J.P.Chalifoux "Ploughing of soft asperities by a hemispherical slider tribology international" Vol.22, No.6, 1989.



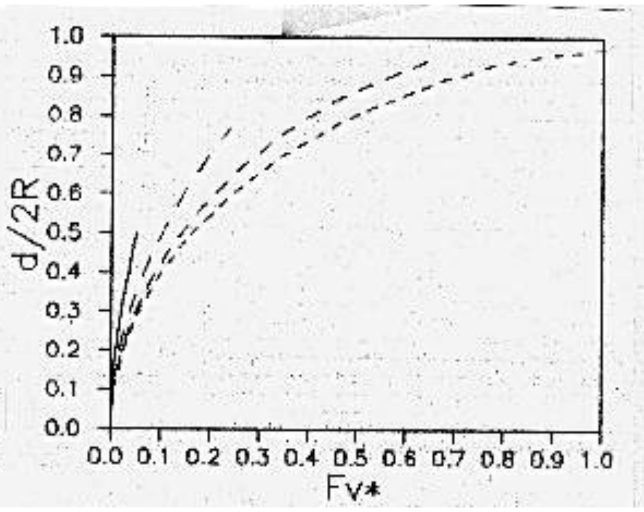
Fig(5.1) Graf of Width of Grooving versus vertical force For Various θ in a Climbing Situation , For n=0



Fig(5.2) Graf of Width of Grooving versus vertical force For Various θ in a Climbing Situation , For n=0.3



Fig(5.4) Graf of Width of Grooving versus vertical force For Various θ in a Climbing Situation , For n=1



Fig(5.3) Graf of Width of Grooving verses vertical force For Various θ in a Climbing Situation , For n=0.6

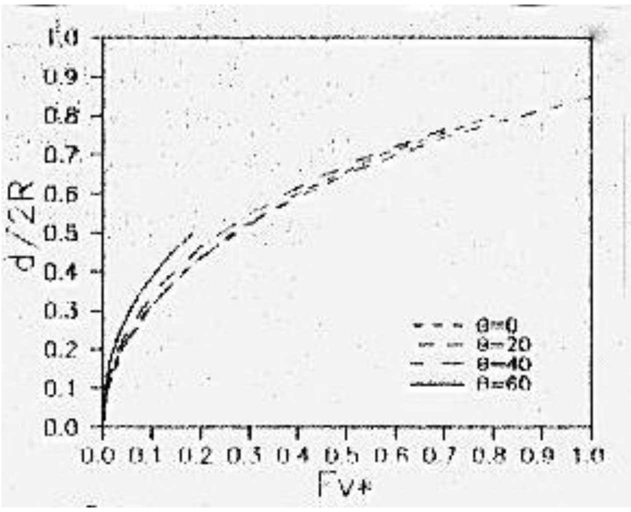


Fig.(6.1) Graf of Width of Grooving Versus vertical Force for Various θ in a Descending Situation for n=0

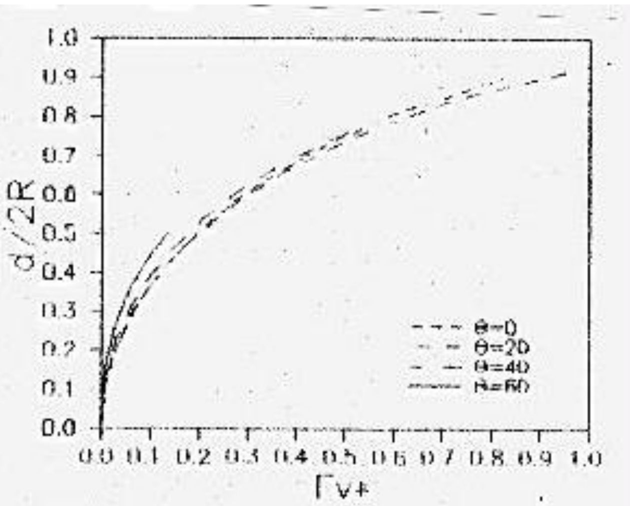


Fig.(6.2) Graf of Width of Grooving Versus vertical Force for Various θ in a Descending Situation for n=0.3

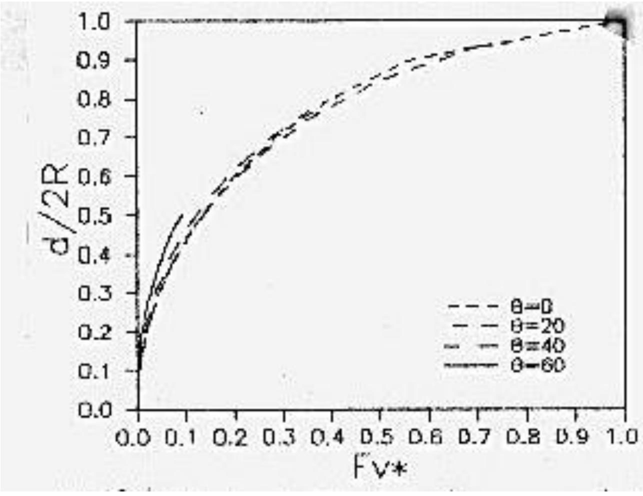


Fig.(6.4) Graf of Width of Grooving Versus vertical Force for Various θ in a Descending Situation for n=1

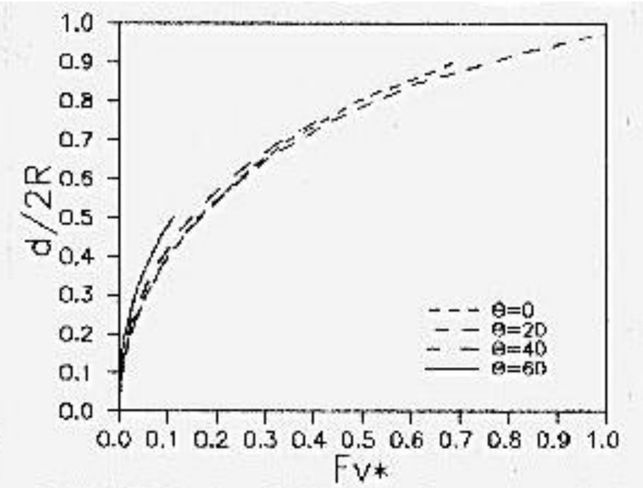


Fig.(6.3) Graf of Width of Grooving Versus vertical Force for Various θ in a Descending Situation for n=0.6

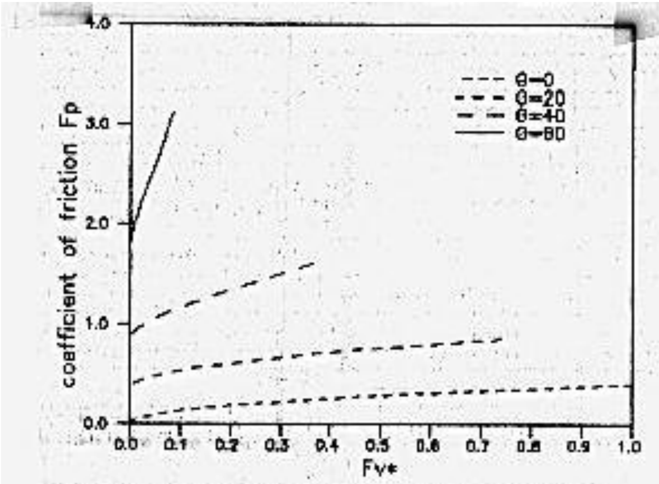


Fig.(7.1) Graf of Friction Coefficient Versus Vertical Force For Various θ in Climbing Situation For n=0

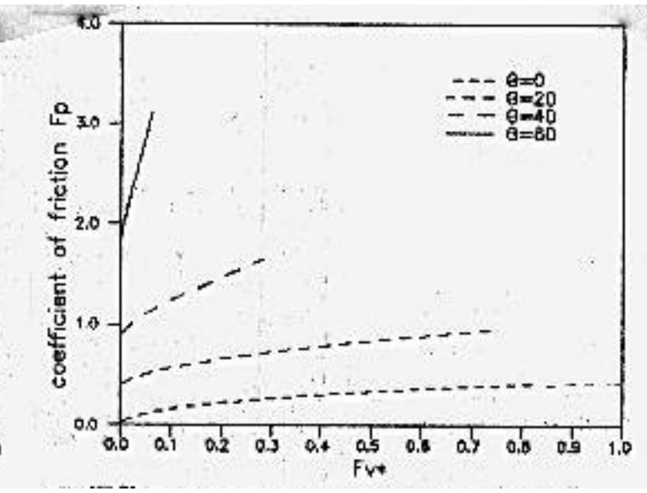


Fig.(7.2) Graf of Friction Coefficient Versus Vertical Force For Various θ in Climbing Situation For n=0.3

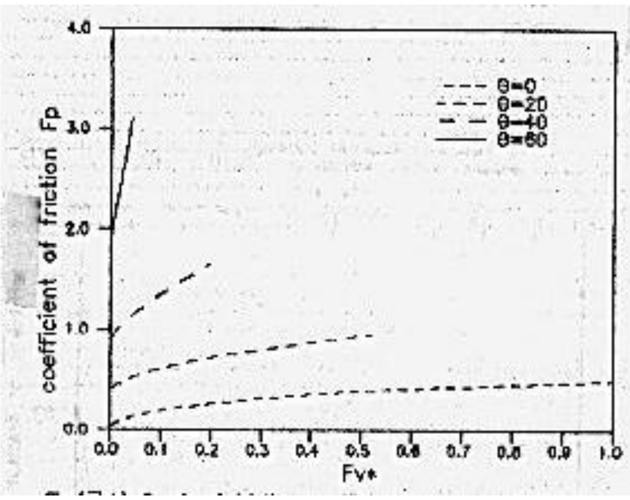


Fig.(7.4) Graf of Friction Coefficient Versus Vertical Force For Various θ in Climbing Situation For n=1

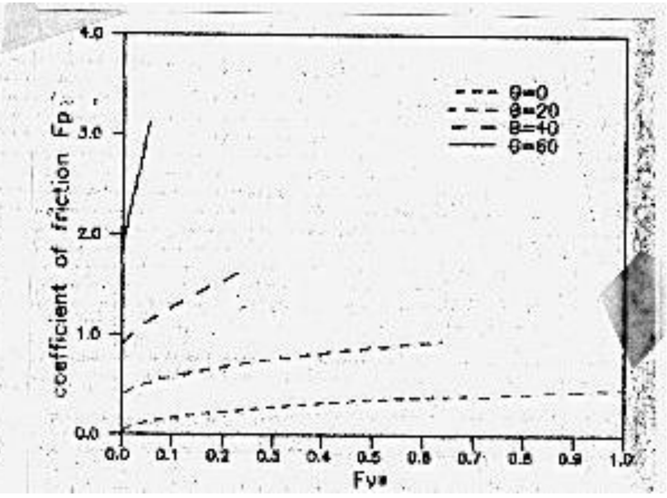


Fig.(7.3) Graf of Friction Coefficient Versus Vertical Force For Various θ in Climbing Situation For n=0.6

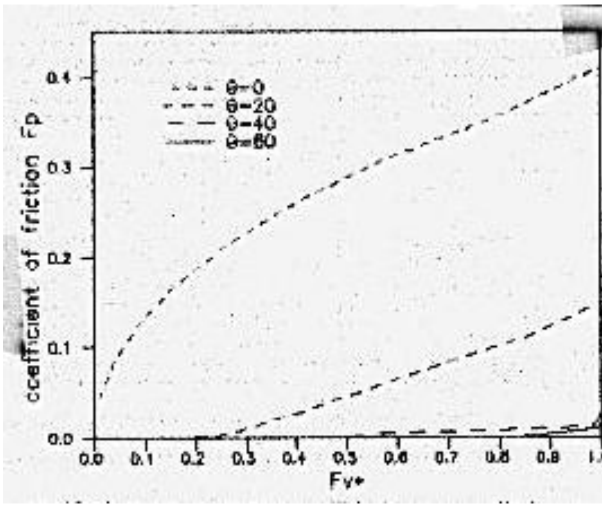


Fig.(8.1) Graph of Friction Versus Vertical Force For Various θ in a Descending Situation For n=0

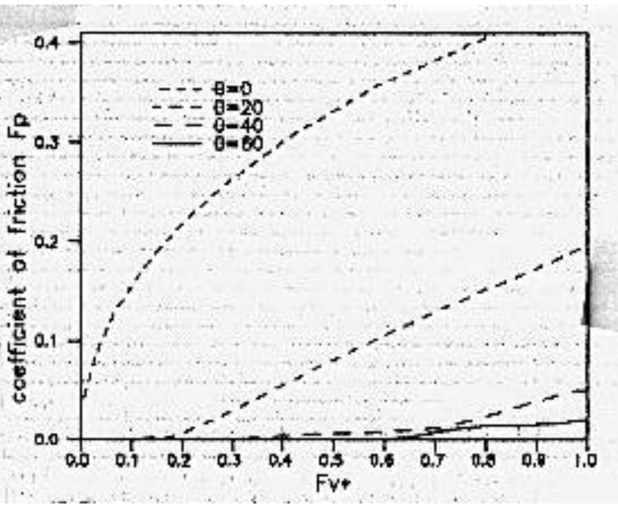


Fig.(8.2) Graph of Friction Versus Vertical Force For Various θ in a Descending Situation For n=0.3

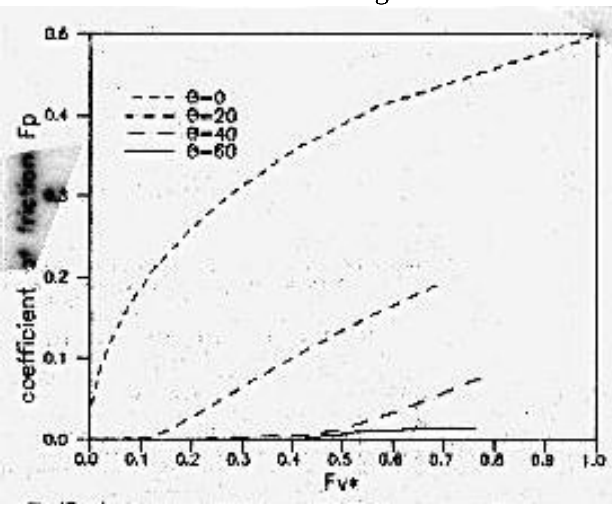


Fig.(8.4) Graph of Friction Versus Vertical Force For Various θ in a Descending Situation For n=1

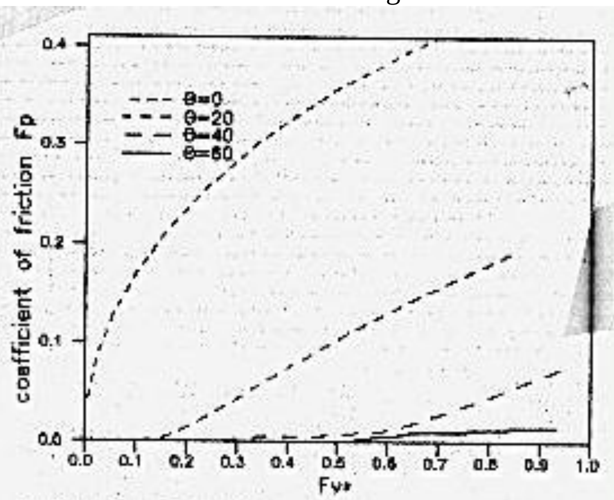


Fig.(8.3) Graph of Friction Versus Vertical Force For Various θ in a Descending Situation For n=0.6

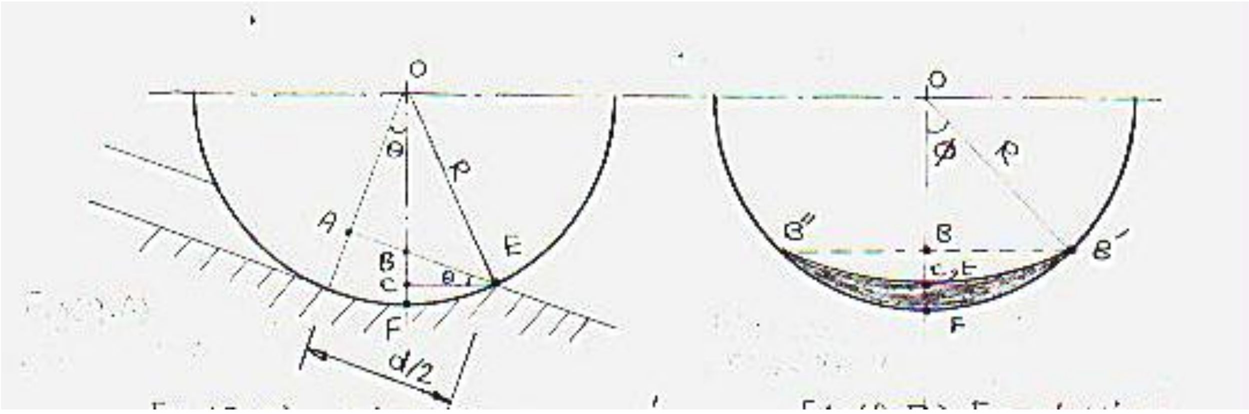
APPENDIX:

Here are the details for derivation of eq(9) to calculate A_{hd} as shown in fig(4). Fig (9) gives an outlines of fig(4) and is used in the following equations.

$$area\, OB''B'O = I = R\cos\phi\, R\sin\phi = \frac{R^2 \sin 2\phi}{2}$$

$$area\, B''BB'CB'' = II = 2(\pi/4)(BC \times BB')$$
$$= (\pi/2)\{(d/2R) - \tan\theta(1-(d/2R)^2)^{0.5}\}R\sin\theta\, R\sin\phi$$

$$area\, B''CB'FB'' = III = R^2\phi - I - II$$
$$= R^2\phi - \frac{R^2 \sin 2\theta}{2} - \frac{R^2\pi}{2}\{(d/2R) - \tan\theta(1-(d/2R)^2)^{0.5}\}\sin\theta \sin\phi$$



Fig(9.A) Side View

Fig(9.B) Front View