A vertical lift digger for harvesting potatoes

C. D. McLEOD, G. C. MISENER, and J. R. CAISSIE

Research Station, Agriculture Canada, Fredericton, NB, Canada E3B 4Z7. *Received 5 August 1987, accepted 4 August 1988.*

McLeod, C. D., Misener, G. C. and Caissie, J. R. 1989. **A vertical lift digger for harvesting potatoes.** Can. Agric. Eng. **31**: 11–14. The concept of elevating potatoes and associated material such as soil directly from the digging shares improves potato harvesters by reducing conveyor lengths, machine weight and power requirements. A prototype unit based on this concept has been built and evaluated, and has proven successful for harvesting potatoes with low injury levels. The key component for elevating potatoes at a 60° angle from the horizontal is a weighted belt that operates on the surface of the digger bed extending the full height required for conveying into a bulk truck. The weight of the belt holds the potatoes in place on the digger bed while aiding soil separation from the potatoes. The depth of material on the bed is reduced by using a high digger bed speed relative to the forward speed which assists the elevation of the material. The paper describes the vertical lift digger giving design criteria and performance details of the machine.

INTRODUCTION

Potatoes travel 17 m on conveyor systems as they pass through a harvester (Hyde et al. 1983). The primary reason for the length of conveyors is to elevate potatoes at a low slope to prevent roll back, as well as to separate loose dirt. It is often difficult to retain sufficient soil on the conveyors to provide cushioning for potatoes in order to minimize injury. Flighted conveyors with steeper inclines can reduce the conveyor length, but the larger clearances require increased drop heights between conveyors, which increases the level of potato injuries. Johnson and Peterson (1976) suggested removing the flights and substituting an anti-roll belt to hold the potatoes on the conveyor surface. The anti-roll belt was made from a solid flexible material that rested on the conveyor surface and was driven by its own drive sprocket such that the contact surfaces between the belt and conveyor were driven in the same direction and at the same speed. The only force the anti-roll belt exerted on the conveyor was weight, and it was this weight that trapped and held objects on the conveyor as they moved up the incline. This unit is now common on side elevators on commercial harvesters.

The Fredericton Research Station has developed specialized potato harvester components with the emphasis on improving the operating efficiency while minimizing potato injury. Prototype harvesters were built so that components such as rotating brushes, vibrating shares, and foam cylinder elevators could be evaluated. The prototypes have consistently removed loose dirt using a combination of webbed conveyor belting, clod rollers and rotating brushes with soil moisture contents ranging from 13 to 28% d.b.. These harvesters utilized only 3 m of webbed conveyor length of which 2.0 m were on the primary digger bed where sieving action was assisted by secondary treatments such as vibrating sieving shares, hydraulic and mechanical shakers (McLeod and Misener 1986). The objective of this study was to design, build, and evaluate a potato harvester that could separate and elevate potatoes directly from the row to the delivery conveyor height, with a minimum conveyor length and a minimum of potato injury.

HARVESTER DESIGN

The design principle involved was to elevate the potatoes directly while providing adequate sieving area for loose soil removal at operating speeds common in Eastern Canada.

Lift angle

The physical conditions that limit the angle of potato lift are the minimum digger bed area required to sieve the soil and the minimum delivery height needed to load trucks. If the minimum bed length is established at 3 m, then for a 60° angle the delivery height is 2.6 m. This height is sufficient to load onto delivery booms on commercial harvesters that were measured at 2.3–2.5 m above the ground. A system was developed to hold tubers and other material on the digger bed surface while elevating at this steep incline.

Weight belt

A flighted or bucketed open webb conveyor could not be used because there was not enough clearance at the digging share where the bed was loaded. An anti-roll type weighted belt was selected as an option to assist elevating tubers, but when operated at a 60° incline special design considerations were required to make it functional including additional weight and flexibility. In order to specify the weight required on this belt to prevent rollback, estimates of the behavior of the material in the potato hill were made. Under conditions where the soil was being agitated and sieved the internal friction of the soil was not considered sufficient to allow a 100-mm-thick layer of material to be elevated from the potato hill, even when compressed between the weight belt and digger bed. However, if this layer was 50 mm thick, it was estimated that larger particles such as the potatoes, clods, and stones would be held by the two surfaces and assist elevating the remaining material. An analysis of potato hill geometry and contents that was done for background on vibrating sieving shares (McLeod and Misener 1986) gave a mean material depth of 100 mm when averaged over the entire row width. The hill height ranged from 0 mm in the bottom of the row to 260 mm at the hill center, and the material had an average density of 1440 kg/m^3. The required bed speed was determined to be twice the forward speed to reduce the average depth of material from 100 mm in the hill to 50 mm on the bed.

The force required to hold a tuber between two flat surfaces at a 60° incline was calculated to 1.1 times the tuber weight assuming a coefficient of friction of 0.55 (Mohsenin 1965). To elevate a 50-mm-thick layer of sharp non-rolling material at a density of 1440 kg/m^3 the required mass per area of the weight belt laying on the horizontal surface was determined to be 79 kg/m^2. The weight belt was designed with pockets oriented at 90° to the direction of travel, and loosely filled with blasting sand to provide the 79 kg/m^2 mass per area. Rollers were used for transferring weight from the returning weight belt to the lower bed in order to provide additional pressure to initiate elevating the hill. The mass per area approaches 200 kg/m^2 at the base of the transfer rollers. The prototype harvester is presented in Fig. 1.

The pockets formed a more positive driving link than a flat belt and combined with the extra transferred weight assisted to spread the deeper hill sections more uniformly across the conveyor bed.

Allowable impacts

An analysis was done on the effects that high digger bed to forward speed ratios have on tuber injury when operating in the 2:1 ratio range. For the purpose of this analysis the energy absorbed by the potato striking the rod at a given relative velocity was considered equal to the energy absorbed when a rod strikes the tubers at the same relative velocity. In other words, for a potato surface not previously deformed, the energy expended accelerating the tuber from zero to a given velocity was considered equivalent to the energy expended decelerating it to zero from the same velocity.

The initial deformation of the tuber at impact was assumed a function of kinetic energy absorbed by the tuber to either decelerate or accelerate it, and that in either case the relative velocity between the tuber and rods approaches zero. In all cases, the tuber is deformed and the rods are not, and the tuber injury sustained is considered a function of the kinetic energy absorbed.

The kinetic energy limit below which no injury was expected to occur was chosen at that velocity obtained when a tuber experienced a 150-mm drop. No injury was found when tubers were dropped 150 mm onto digger-bed-type rods, even though the tuber size and thus the kinetic energy varried (Mohsenin 1970). At this upper limit there is a larger margin of safety for the smaller tubers.

The behavior of tubers at impact in the soil was considered equivalent to that for tubers aboveground, except the tuber was assumed to act with a larger mass. There is a volume of soil surrounding the tuber moving with it which effectively increases the mass. This soil volume was estimated to be twice the tuber volume, and approximately three times its mass. Thus, a tuber with mass M would have an effective mass of $4M$ in the soil.

Maximum kinetic energy absorbed by the tuber dropping 150 mm onto rods for injury-free conditions:

$$KE = 1/2\ MV^2 \tag{1}$$

where:
M = mass of tuber, and
V = relative speed at impact between tuber and rods after the 150-mm drop.

For tubers in the soil, the kinetic energy absorbed by the tuber:

$$KE = 1/2\ (4M)\ VC^2 \tag{2}$$

where:
$4M$ = mass of tuber with soil; and
VC = relative speed at impact between the tuber and rods.

For the condition where the kinetic energy terms are equal at the maximum injury free limit:

$$VR = VC = V/2 \tag{3}$$

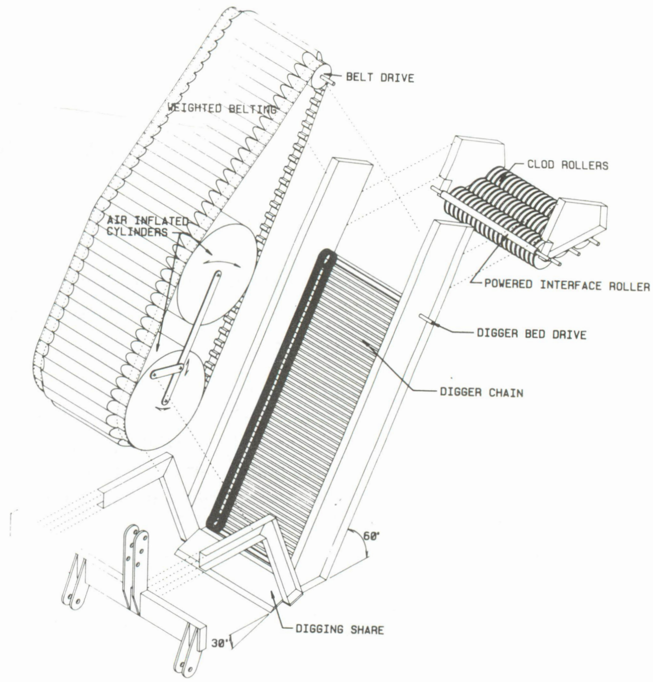

Figure 1. Vertical lift digger test model.

where:
VR = critical impact speed in soil at the injury-free limit.

The impact velocity is determined by the vector sum of the velocities of the bed and machine velocities.

$\vec{VB}$ = velocity of the digger bed relative to the machine at the tuber contact point;
$\vec{VF}$ = velocity of the machine relative to the tuber;
$\vec{VRL}$ = resulting relative velocity vector between the tuber and the digger bed rods;
α = contact angle between $\vec{VF}$ and $\vec{VB}$.

$$(VRL)^2 = [VB - VF\ \mathrm{COS}\ (\alpha)]^2 + [VF\ \mathrm{SIN}\ (\alpha)]^2 \tag{4}$$

Solving for digger bed/forward speed ratio:

$$\frac{VB}{VF} = \mathrm{COS}\ (\alpha) + \sqrt{\left(\frac{VR}{VF}\right)^2 - \mathrm{SIN}\ (\alpha)^2} \tag{5}$$

At the injury-free limit, the relative speed at impact approaches the critical impact speed which is 858 mm/s or 3.09 km/h after a 150-mm drop.

In practical situations the contact angle changes when the tuber-rod contact location changes from points on the rounded surface at the head roll to points on the flat main bed. A graph of Eq. 5 for a family of contact angles where VR = 3.10 km/h is shown in Fig. 2.

Harvester description

The harvester was three-point hitch mounted with telescoping wheels for setting and controlling the digging depth. The digger bed and weighted anti-roll belt were driven by a hydraulic motor powered from the remote hydraulic system on the tractor. An adjustable flow diverter was utilized to establish the final bed speeds. The weight belt was driven at the same speed as the digger bed to prevent relative motions between the surfaces and skinning of the potatoes. Two inflated rubber rollers transmitted

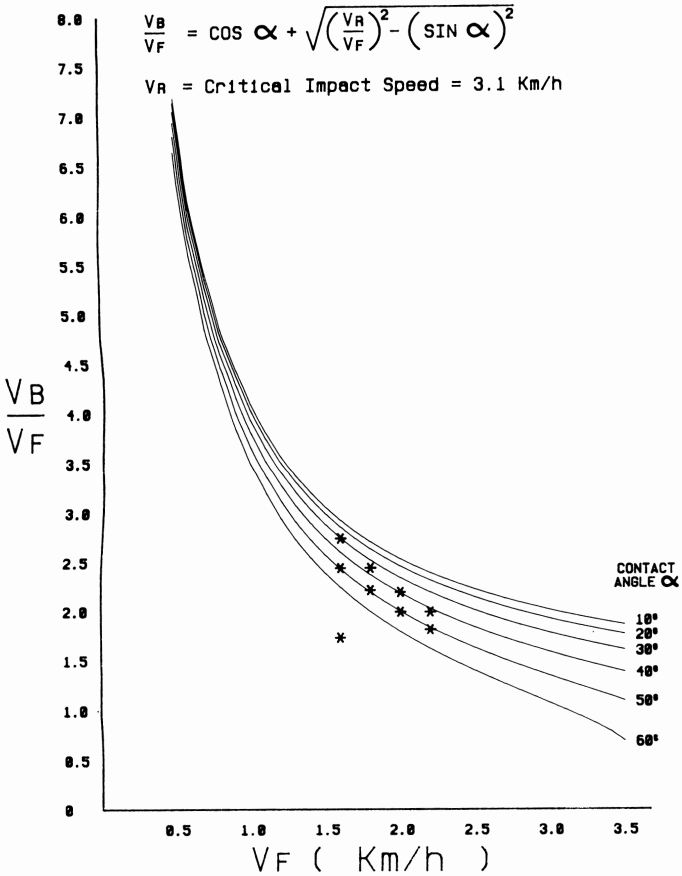

Figure 2. Graph of the maximum digger bed/forward speed ratio predicted for injury-free tubers as a function of forward speed. Field test points are indicated.

the weight from the return portion of the weight belt to the lower portion of the bed to assist elevating the material as it first feeds onto the digger (Fig. 1). Clod rollers were used after the main bed to increase sieving, and to provide a horizontal surface from which samples could be delivered. A driven interface roller reduced the drop between the digger bed and clod rollers.

TEST PROCEDURE

The prototype harvester was evaluated under field conditions in order to determine its effectiveness for elevating potatoes, while minimizing tuber injury.

The harvester field tests were conducted at four forward speeds and three digger bed speeds. The bed speeds were 2.8, 4.0, and 4.4 km/h while the forward speeds were set at 1.6, 1.8, 2.0, and 2.2 km/h. After 5 m of travel, a sampling container was placed behind the clod roller and left there for a distance of 2 m collecting a potato sample of approximately 5 kg. This process was replicated three times for each forward and bed speed combination.

All tests were conducted at speed ratios clustered in a narrow range around the 2:1 ratio and near the predicted injury-free limit for an estimated contact angle range between 40 and 50°. The tests were not expanded to larger ranges outside the predicted limit, because there was no previous experience with ratios anywhere near as large as those being tested.

After harvesting, the potato tops were removed from each sample container and the weights of soil, clods, potatoes, and rocks were recorded along with soil temperature and soil moisture. The potatoes were stored for a month to allow suberization and then assessed for damage.

Tuber damage was determined using a potato peeler to remove a slice approximately 3 mm thick with each stroke. Damage was classified as follows (Thornton 1969): (a) undamaged, (b) scuffed or skinned — skin only broken, (c) slightly or peeler — flesh damage removed by a 3-mm-deep stroke of the peeler, and (d) severely damaged — damage to flesh which was not removed with the one peeler stroke. A damage index was then calculated based on the percentage of tubers in each category multiplied by 0, 1, 3, and 7, respectively, and then added to give a total index (McGechan 1980). Blackspot was not measured because it was not expected to be a major factor under the test conditions. The results were then processed using a computerized statistical model developed by SAS Institute Inc., Cary, NC, 27511, U.S.A. and the results are summarized in Table 1. All potatoes were of the Russet Burbank variety.

RESULTS AND DISCUSSION

The results of plotting the digger bed to forward speed ratio versus forward speed (Fig. 2) suggests it might be possible to operate with high ratios, particularily when lower forward speeds such as those common in Eastern Canada are used. By extending the solution to the equation on this graph to forward speeds common in the Western United States (3–6 km/h), and using contact angles between 10 and 20° expected on commercial harvesters, the equation predicts that the digger bed to forward speed ratios will reduce, approaching 1:1 at large forward speeds. The resulting ratios would be compatible with the recommendations forwarded from the U.S. work (Peterson 1975; Hyde et al. 1983) based on soil loading and damage relationships.

There were two operating parameters that were significantly correlated to the potato damage index, neither of which were machine variables. Soil temperature significantly correlated to the damage index and, as expected, the damage index for the tubers decreased as the temperature increased. The other parameter was the amount of rock, and the damage index increased as the rock levels increased. This was also expected and rock removal developments for potato harvesters remain a priority, with emphasis on developing the ability to separate rocks, before they contact tubers. The other environmental factors such as soil moisture, and the soil sample weight were not significantly correlated to the damage index. The soil moisture contents experienced during the tests were normal for Eastern Canadian conditions, and it appeared that sufficient soil was sieved during the testing to overcome any cushioning effects that might unduly influence the damage index levels.

Table I. Correlation coefficients of damage index to harvesting parameter conditions

Variable	Average	Range	*r*
Forward speed (km/h)	1.84	1.60– 2.20	0.04
Digger bed speed (km/h)	4.02	2.77– 4.38	0.09
Ratio: digger bed speed / forward speed	2.23	1.73– 2.74	0.10
Soil moisture % (DB)	18.84	15.30–24.40	0.30
Soil temperature (°C)	12.30	9.50–13.0	−0.46**
Rock weight (kg)	3.18	0–13.63	0.43**
Soil weight (kg)	4.20	0.40– 8.97	−0.03
Potato weight (kg)	5.43	2.82– 8.10	−0.11

**Significant at 1% level.

The machine-adjustable operating parameters did not significantly correlate to the potato damage index. These parameters included digger bed speed, forward speed and the resulting ratio. These results agreed with the theoretical prediction that mechanical damage could be avoided when the impacts between rods and tubers occurred at kinetic energy levels less than those encountered with a 150-mm drop. The results also confirm that speed ratios of 2.74:1 are technically possible when lower forward speeds are used.

The damage index was less than the 200–500 level measured in New Brunswick with commercial harvesters, and when the below normal temperatures are considered there is a good potential for less tuber injury in a normal year. The damage index averaged 147.80 and ranged from 37.6 to 362.97.

The prototype harvester successfully elevated the tubers at the 60° incline, indicating that there was sufficient weight on the anti-roll to accelerate, separate, and elevate the potato hill material. There was some flow of material forward as well as sideways from the potato hill center where the material was deepest; however, there was never enough to spill tubers around the share edges at the harvester mouth.

Work is required to measure the effect surface loading has on sieving rates for adjusting bed/forward speed ratios and optimizing harvester widths, bed lengths, and speeds.

CONCLUSIONS

It is technically possible to elevate potatoes directly from the hill to the harvester delivery boom by assisting a regular digger bed conveyor with a weighted anti-roll belt. This was done with minimal tuber injury while the digger bed operated at high speeds and the product was lifted at a steep angle.

Test results indicated that high bed speed to forward speed ratios are possible at low forward speeds, without affecting tuber injury levels which agreed with the theoretical predictions for the conditions encountered. The results also confirmed the fact that tuber temperature and the presence of rock both influence the amount of tuber injury sustained during the harvesting process. The amount of rock present has a direct influence while higher temperatures reduce the injury levels.

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