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ROPS designs to protect operators during agricultural tractor rollovers

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Abstract

Although it is well known that properly used Rollover Protective Structures (ROPS) can virtually prevent agricultural tractor rollover fatalities, the U.S. still has hundreds of these fatalities per year. An estimated 1.6 million tractors are not equipped with ROPS. Many of these tractors do not have ROPS commercially available although they were originally designed to support a ROPS. Some tractors have foldable ROPS that are not used properly. Other ROPS, although meet appropriate performance standards, are not effective at eliminating continuous rolls.

To meet this need, a Computer-based ROPS Design Program (CRDP) was developed to quickly generate ROPS designs based on agricultural tractor weights and dimensions. The ROPS designed with the CRDP for the Allis Chalmers 5040 tractor successfully passed the SAE J2194 static longitudinal, transverse, and vertical tests. A simple foldable ROPS lift assist was designed and tested to ease in the raising and lowering of ROPS; decreasing the raising torque from 90 Nm to less than 50 Nm, while also lowering the resisting torque to lower the ROPS. A model to determine the critical ROPS height CRH based on off-road vehicle dimensions and center of gravity (CG) height was developed and evaluated.

Keywords

ROPS; Tractor rollover; Foldable ROPS

1. Introduction

A Rollover Protective Structure (ROPS) is a mechanical structure which absorbs a portion of the impact energy generated by the tractor weight in the rollover accident. The ROPS decreases the possibility of severe human injuries by providing a clearance zone to protect the operator within the ROPS envelope. It is well known that tractor rollovers are the leading cause of U.S. agricultural fatalities (NORA AgFF Sector Council, 2008), and a tractor ROPS and seatbelt virtually eliminates that problem. While ROPS are more prevalent on agricultural tractors in the United States, an estimated 1.6 million tractors are still not equipped with ROPS. Many of these tractors do not have ROPS commercially available although they were originally designed to support a ROPS. There is a need to quickly develop ROPS designs in order to manufacture ROPS meeting current ROPS standards.

Some ROPS on tractors are not used properly. Foldable ROPS are becoming very popular and are heavily used in agriculture where low trees, overhead obstruction, and limited access storage promote their usage. In addition, foldable ROPS are now considered the commercial state-of-the-art in operator protection. If a foldable ROPS is not offered, and an operator is likely to take off the ROPS to fit in low clearance structures. Thus, manufacturer have incentive to provide the foldable ROPS option. So then if a foldable ROPS is required for a tractor, it does not make sense to also provide the fixed ROPS option. For this reason, more foldable ROPS are being used and are prevalent in the Agricultural tractor community (Myers, 2015). But the problem exists when the ROPS are left folded down. Myers (2009) states that “An argument against ROPS is overhead obstructions, such as collisions with tree limbs. The adaptation of a foldable ROPS has been used as a solution to the tree limb obstruction problem. Nevertheless, foldable ROPS are problematic since they are easily left in a folded position.”

Tractor rollovers when ROPS are folded down are causing fatalities in the U.S. In a March 2015 review of NIOSH Fatality Assessment and Control Evaluation (FACE) reports, there were no rollover fatalities with tractors with ROPS folded down prior to 2003 (NIOSH FACE, 2015). Since 2005, 25% of the rollover fatalities occurred with ROPS folded down. And since 2010, 50% of tractor rollover fatalities reported occurred with tractors with the ROPS folded down. Although this is a small sample size, the trend is disturbing.

The survey conducted by European Commission members showed that in tractor rollover accidents, 40% of fatalities and serious injuries happened when the ROPS was in inoperative (folded) position (Hoy, 2009). Pessina et al. (2015) reported that 30% of the tractor rollover fatalities in Italy from 2008 to 2014 result from ROPS in the folded down position.

According to a ROPS manual (Wright Manufacturing. Inc., 2014) the statement is provided – “If ROPS is a folding ROPS, ROPS should be in the upright position and pinned when operating the machine.” Unfortunately this does not always happen. Foldable ROPS are difficult to fold up and down, so they are frequently left folded down during operation.

The operation needed to fold up a ROPS includes:

1. Stop tractor and engine.
2. Remove seatbelt.
3. Exit from tractor.
4. Move to back of tractor.
5. Detach quick-lock pins (linchpins or clip pins) on both sides of ROPS.
6. Pull out the hitch pins on both sides of ROPS. May need to shake ROPS or use pliers to remove pins.

7. Fold up the ROPS (overcoming the weight and frictional forces and usually requires standing on the drawbar for larger tractors).
8. Hold the ROPS up while you align holes in raised position.
9. Insert hitch pins both sides.
10. Insert quick-lock pins both sides.
11. Climb back into seat.
12. Fasten safety belt.
13. Start engine and drive off.

Then the process needs to be reversed to fold the ROPS down upon approaching another obstacle. Lowering and raising the ROPS is time consuming and strenuous therefore, many operators prefer to leave the foldable ROPS in inoperative (folded) position.

Alternative options for manually foldable ROPS exist, including: (1) automatically deployable ROPS (Powers et al., 2001), and (2) powered foldable ROPS (Ayers et al., 2012). Both have promise in future ROPS designs, but are impractical to retrofit on the existing foldable ROPS currently in operation, and due to their cost and complexity have not reached commercial viability (Myers, 2015).

Organisation for the Economic Co-operation and Development (OECD) Code 7 defines the maximum foldable ROPS actuation forces for narrow track tractors (OECD, 2017). The allowable forces by operator to actuate (raise and lower) foldable ROPS has been identified and range from 100 N in the comfort zone to 50 N in the accessible zone with forward leaning of the body. The forces may be increased by 50 N at specific locations. These forces are often exceeded with large foldable ROPS. Engineering control designs are needed to reduce the foldable ROPS actuation forces for large ROPS.

ROPS are designed to protect the operator in the event of a rollover, but the U.S. ROPS standards do not necessarily prevent the continuous roll of the tractor down a slope. Tractors are designed to operate at a slope of 20 percent or less (Ebert et al., 2006). A continuous (greater than 90 degrees) vehicle rollover increases the opportunity for operator injury. Preventing a continuous roll can be accomplished by increasing the ROPS height. A critical ROPS height (CRH) is the ROPS height that prevents a continuous side roll on a specific slope. The CRH can be influenced by the tractor center of gravity (CG) height. The influence of tractor CG height on CRH, and thus continuous roll potential, needs to be explored.

2. Computer-based ROPS design program

A computer-based ROPS design program was developed to quickly generate ROPS designs based on tractor weights and dimensions (Ayers et al., 2016). The final product from the program is the ROPS design drawings with specifications that can be used to construct the ROPS. The ROPS would then need to be tested to assure it meet the appropriate ROPS standard. The final required tractor dimension inputs and ROPS design outputs, for the

Computer-based ROPS Design Program (CRDP) have been established using Microsoft Excel program. The model input parameters (46 tractor dimensions and tractor mass) were organized into multiple input sheets and have been used to collect tractor and ROPS dimensions (Fig. 1).

Model parameter inputs have been determined for 16 tractor/ROPS combinations and have been included into the tractor/ROPS dimension database. This database is used to generate the required ROPS dimensions. Fig. 2 shows an example of the relationship between the tractor and ROPS dimensions.

The 28 required ROPS design dimensions were defined and incorporated into the ROPS output CAD drawing (within Excel), which are used for ROPS construction. The final ROPS design fabrication drawings have been included in the Computer-based ROPS Design Program (CRDP) (Ayers et al., 2016). This includes drawing of the posts, crossbeam, baseplates, corner braces, and strapping (Fig. 3). ROPS construction and assembly drawing are also provided (Fig. 4).

Using the CRDP and acquired tractor dimensions, a ROPS for an Allis Chalmers 5040 tractor was designed and successfully constructed using a local fabricator. The Allis Chalmers tractor was chosen as it was identified as a common tractor without a commercially available ROPS design. The CRDP provides the required ROPS materials and estimated costs (Fig. 5). The actual ROPS materials and machining (cutting, drilling, and welding) costs were documented and was less than US$600.

Static ROPS performance tests (transverse, longitudinal and vertical) based on SAE J2194 were conducted on the Allis Chalmers 5040 ROPS on August 26, 2014 at the ROPS test facility at FEMCO Inc, in McPherson, KS (SAE, 2009). Fig. 6 shows the results for the longitudinal static test. Based on the tractor reference weight of 1842 kg, the required energy absorption was 2578.8 J. The ROPS absorbed sufficient energy at a deflection of 21.6 cm, well below the allowable deflection of 42.0 cm. Based on all the test results (longitudinal, transverse and vertical), the ROPS met the energy and load requirements at a deflection less than the allowable deflection, indicating the ROPS passed the SAE J2194 static tests (Ayers et al., 2016). In this study, the CRDP was seen as an effective tool to easily design ROPS for tractors that do not currently have ROPS designs.

3. Assisted foldable ROPS

Large and heavy foldable ROPS may produce actuation forces greater than the forces stipulated in the OECD Code 7 (OECD, 2017). If the ROPS actuation forces are too high, a coil spring lift assist design can be implemented to reduce the actuation forces. As the ROPS is lowered, the energy is stored in the coil spring and released to assist the raising of the foldable ROPS. The coil spring design is specific for each foldable ROPS. This is due to the different ROPS foldable section weights and orientation. The force (or torque) to lift a ROPS is dependent on the ROPS folding section weight, center of gravity, and friction at the pivot location. Accurate measurement of weights and location of the center of gravity of the foldable ROPS section are needed. A program was generated to determine these weights and locations based on ROPS dimensions (width, length, tube section and thickness) and material density. Once the estimated torque requirement and ROPS orientations are known, the appropriate coil spring can be designed. Coil (torsion) spring rates (torque/angle) is dependent on coil material, wire diameter, coil inside diameter, and number of active coils. Proper design is needed to assure the material remains in the elastic range under the applied torque and does not fail (i.e. reach the yield stress).

The innovation of the coil spring lift assist design for foldable ROPS is:

1. It does not require an external power source and can be implemented manually.

2. It can be used on new ROPS, or retrofitted to existing foldable ROPS design, using a pivot bolt extension.

3. It is simple and relatively low cost.

4. Guidelines can be developed to choose the proper coil spring design based on ROPS weights and dimensions.

5. It can be incorporated with a lever design and operated from the tractor seat.

One factor to consider in designing a foldable ROPS lift assist is that the integrity of the ROPS cannot be compromised. Modifications of the ROPS, such as drilling, welding, and mounting of structures affect the ROPS performance and must be avoided. Mounting of lift assist devices (gas springs, extension springs) require rigid attachment to the ROPS which can affect ROPS performance and nullify the ROPS certification. Pivot pin attached torsion springs, with properly designed engagement angles, do not engage the foldable ROPS when in the upright protective position and do not compromise the integrity of the ROPS or invalidate the ROPS certification.

A measurement system described by Khorsandi et al. (2016) was used to determine the torques to actuate (raise and lower) a John Deere ROPS (model S-e1–0095, serial number 00544, for tractor models 4120, 4320, 4520, 4720) from – 40 degrees (down) to the 90 degrees (up) (Fig. 7). For this ROPS dimension (with a 0.60 m distance from the foldable pivot point to the top of the ROPS grasping area) the experimentally measured actuation torque (over 90 Nm) is above the maximum torques suggested in the proposed OECD Code 7 (60 Nm). This demonstrates the difficulty for the operator to actuate the ROPS and the need for a lift assist to reduce the required forces. Using the weights and locations based on ROPS dimensions (width, length, tube section and thickness) and material density produced theoretical actuation torques (without coil spring) lower than the measured torques (Fig. 7). Note the increase in the measured torques above the theoretical values demonstrates the influence of friction at the pivot pins on actuation force measurement. To reduce the actuation torques, a ROPS lift assist was designed using four coil springs, two mounted to each pivot pin. The ASTM A228 high-carbon steel coil springs were 10 turn, ¼ inch (0.63 cm) diameter with an inside coil diameter of 2 inch (5.1 cm). They effectively decreased the actuation torques down below 50 Nm and below the OECD Code 7 requirement. This shows the value of the lift assist to reduce foldable ROPS actuation forces. In addition, the lift assist coil springs lowered the resisting torque required to support the lowering of the foldable ROPS (Fig. 8). Note that the resisting torque is less than the theoretical torque (without coil spring) due to the friction at the pivot pins holding up the ROPS as it is being lowered.

4. Critical ROPS height

ROPS not only protect the operator during a tractor rollover but they can also avoid a continuous side roll down a slope. A model developed by Wang (2005) was used to evaluate the continuous roll characteristics of a John Deere model F925 industrial tractor (mower) with ROPS. The model analyzes the tractor dimensions and balances the tractor potential and kinetic energies to determine if a continuous roll occurs after the initial ROPS impact. The model was validated with multiple rollovers using various ROPS heights on a 40 degree side slope. The critical ROPS height (CRH) or the ROPS height that will prevent a continuous roll can be accurately determined (Wang, 2005).

Recent concerns about vehicle stability angle and the need to lower the vehicle CG height to reduce the initial roll, can influence the opportunity for continuous roll. The continuous roll model was used to determine the influence of CG height on the CRH. Fig. 9 shows that as CG height increases (making the tractor less stable for the initial overturn) the critical ROPS height increases (indicating the tractor is more likely to continuously roll). A CG height balance is required to both reduce the opportunity for the initial roll and also avoid a continuous roll situation.

5. Conclusions

These studies have investigated the ROPS design for tractors to help protect operators during a tractor rollover. The CRDP has shown to be effective in designing ROPS that meet the SAE J2194 ROPS static standard tests. Static laboratory performance testing based on SAE J2194 has validated the ROPS designs. Foldable ROPS lift assists have been shown to be effective to lower the actuation forces required to raise a ROPS by nearly 50% and to within the OECD Code 7 recommended forces. A continuous tractor roll model was applied to determine the influence of tractor center of gravity (CG) height on the critical ROPS height (CRH). The model predicts that the higher the CG height, the more likely a continuous roll will occur, requiring a taller ROPS height to stop the roll. These finding are useful in future ROPS designs and agricultural tractor operator protection.

Acknowledgements

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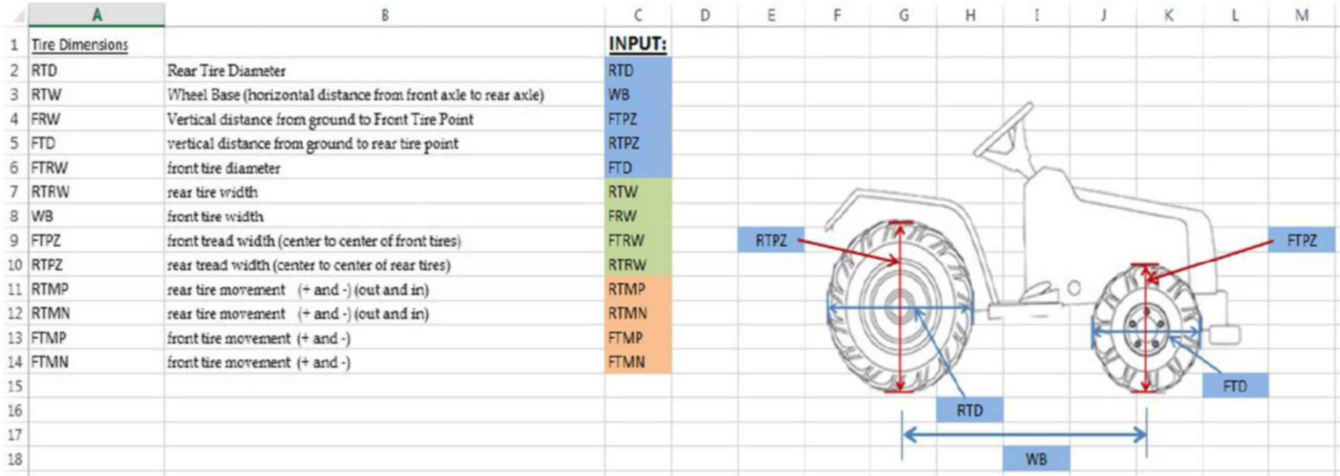

	A	B	C
1	Tire Dimensions		INPUT:
2	RTD	Rear Tire Diameter	RTD
3	RTW	Wheel Base (horizontal distance from front axle to rear axle)	WB
4	FRW	Vertical distance from ground to Front Tire Point	FTPZ
5	FTD	vertical distance from ground to rear tire point	RTPZ
6	FTRW	front tire diameter	FTD
7	RTRW	rear tire width	RTW
8	WB	front tire width	FRW
9	FTPZ	front tread width (center to center of front tires)	FTRW
10	RTPZ	rear tread width (center to center of rear tires)	RTRW
11	RTMP	rear tire movement (+ and -) (out and in)	RTMP
12	RTMN	rear tire movement (+ and -) (out and in)	RTMN
13	FTMP	front tire movement (+ and -)	FTMP
14	FTMN	front tire movement (+ and -)	FTMN

Fig. 1.
Example of tractor dimension inputs for CRDP (units in inches and pounds).

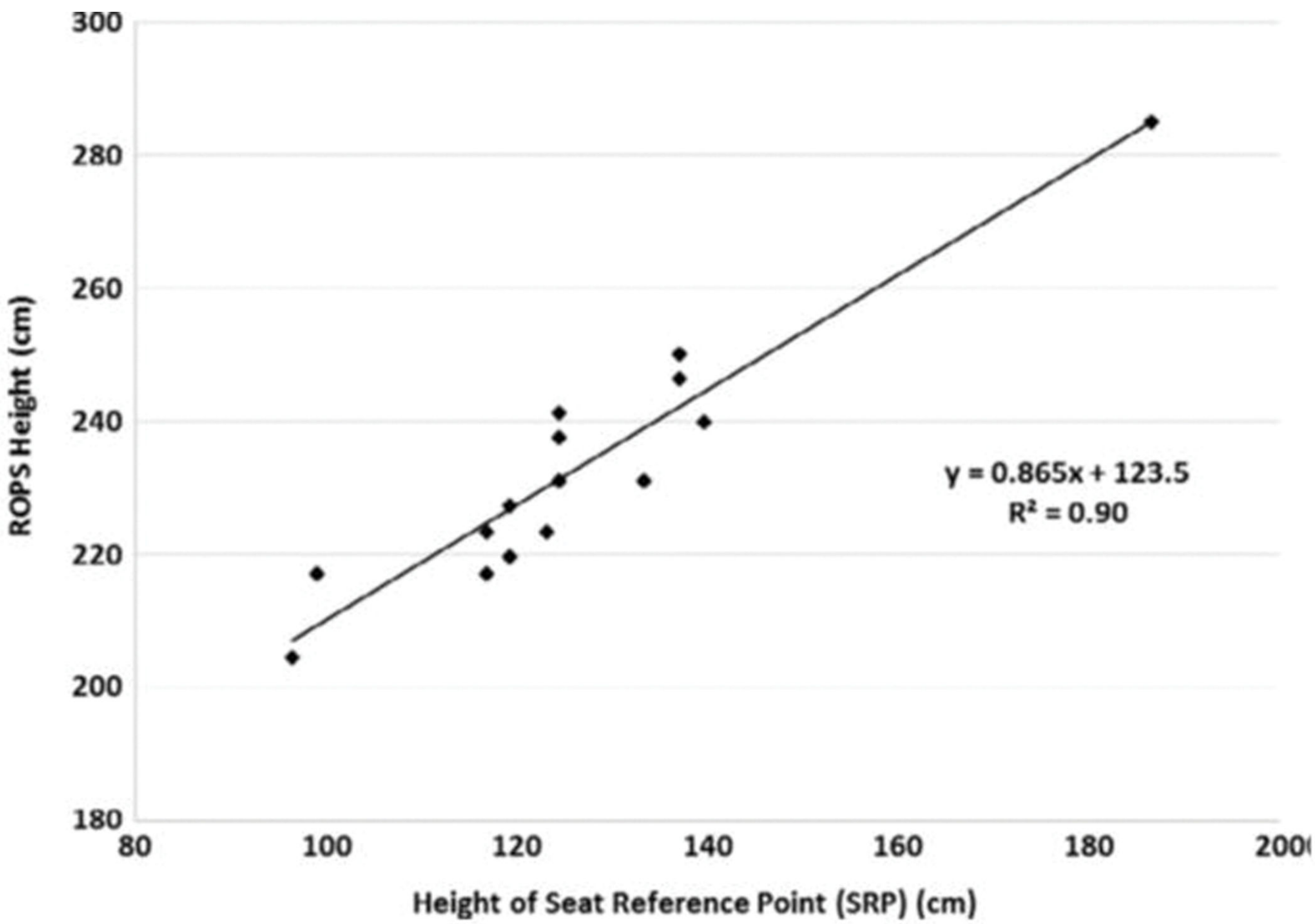

Fig. 2.
Relationship between tractor dimensions and ROPS dimensions.

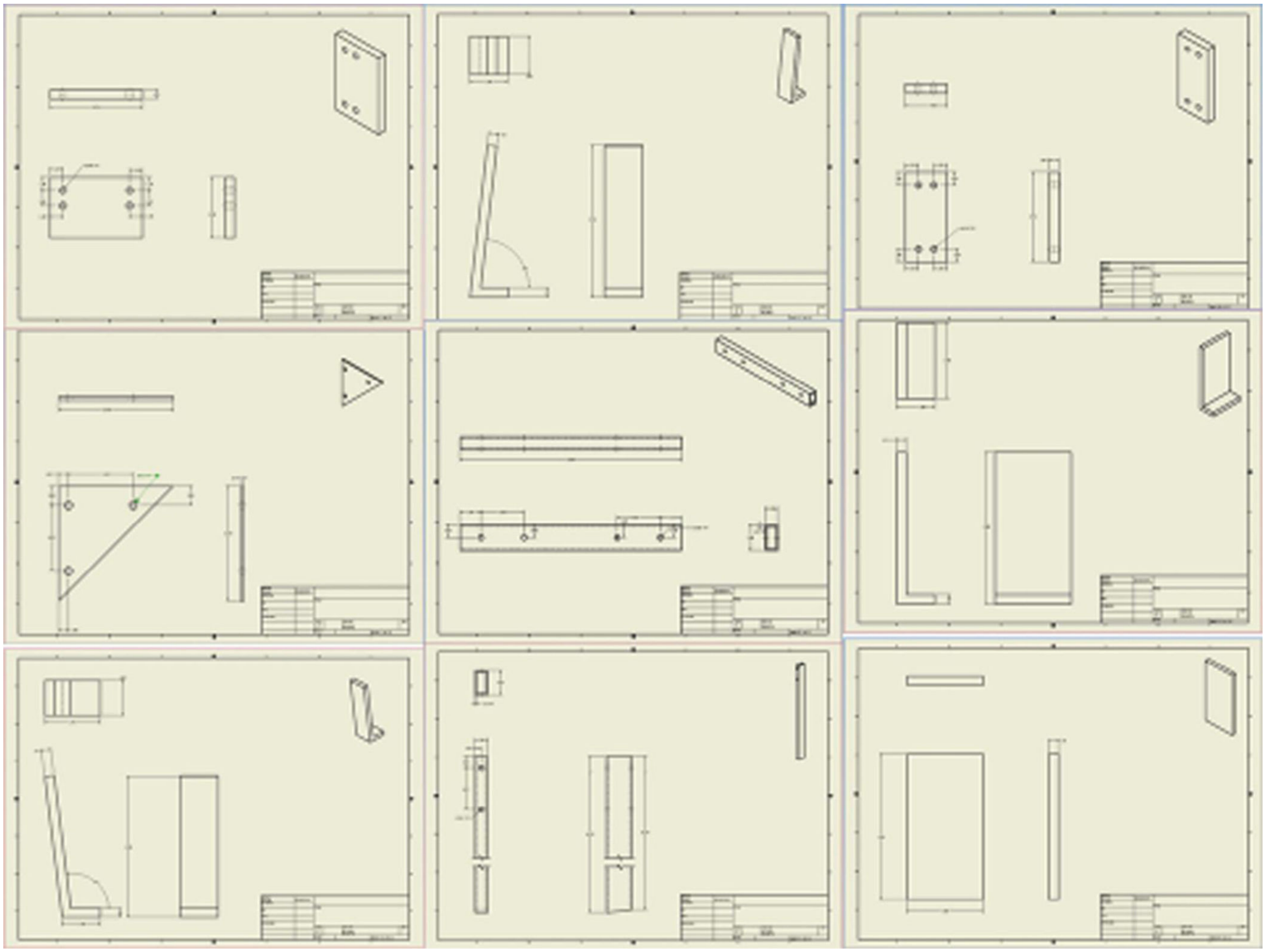

Fig. 3.
Individual ROPS component drawings.

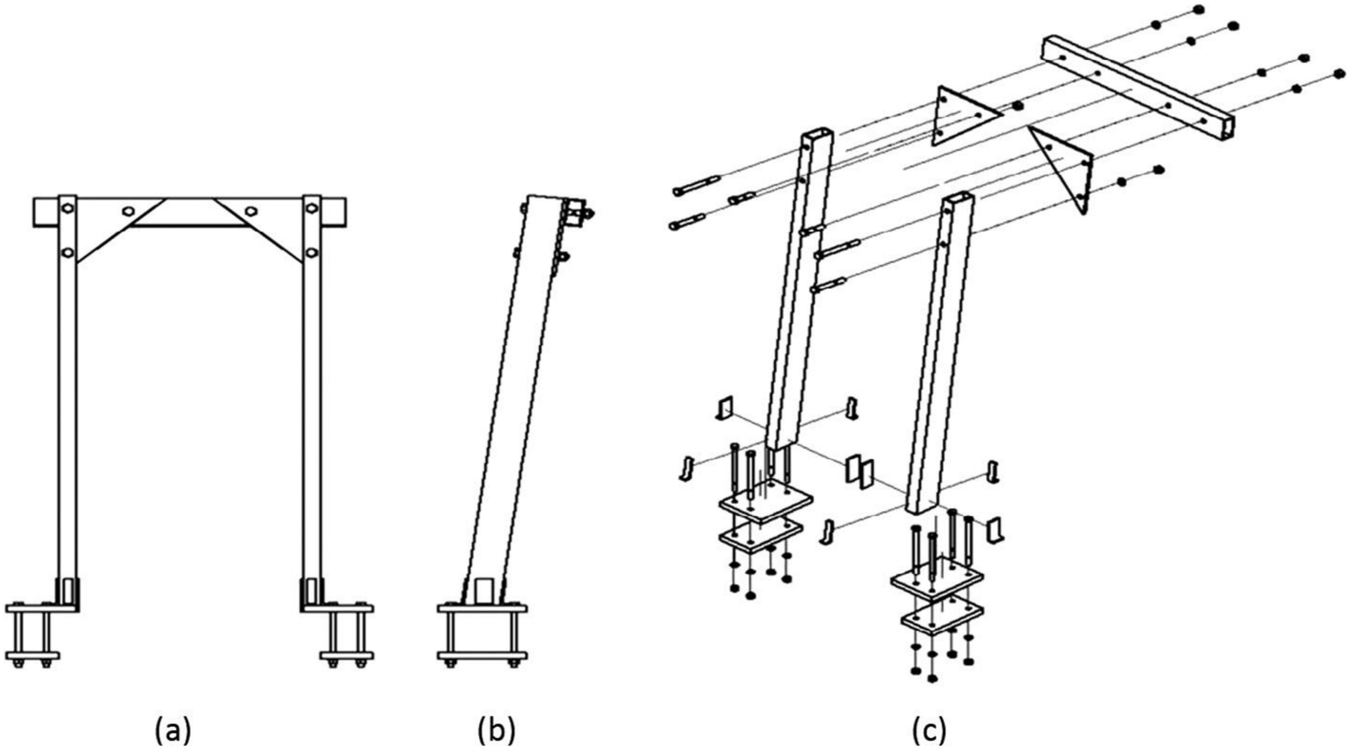

Fig. 4.
ROPS assembly drawing views (a) front, (b) side, (c) exploded.

	A	B	C	D	E	F	G	H	I	J
1	**Summary of Materials and Cost (Length in inches)**									
2										
3	**ROPS Tubing**									
4	Number	Thickness	Lateral box dimension	Longitudinal box dimension	Length	Part	Price			
5	2	0.25	2	4	65.3	posts	196.03			
6	1	0.25	2	4	31.0	crossbeam	46.50			
7										
8	**Baseplates**									
9	Number	Thickness	X dimension	Y dimension	Part		Price			
10	2	1	9	6.125	Top Baseplate		60.64			
11	2	1	9	4.75	Bottom Baseplate		47.03			
12										
13	**Strapping**									
14	Number	Thickness	Length	Width	Part		Price			
15	6	0.25	5	1.5	Baseplate Strapping		5.08			
16	2	0.25	5	1.5	Baseplate Strapping		1.69			
17	4	0.25	4	4	Crossbeam Strapping		7.23			
18										
19	**Bolts**									
20	Number	Diameter	Bolt Grade	Length	Part		Price			
21	8	0.625	8	10	Baseplate Bolt		54.72			
22										
23										
24						Total:	418.91			
25										
26										

Fig. 5.
Spreadsheet with ROPS materials and estimated pricing in U.S. dollars ($).

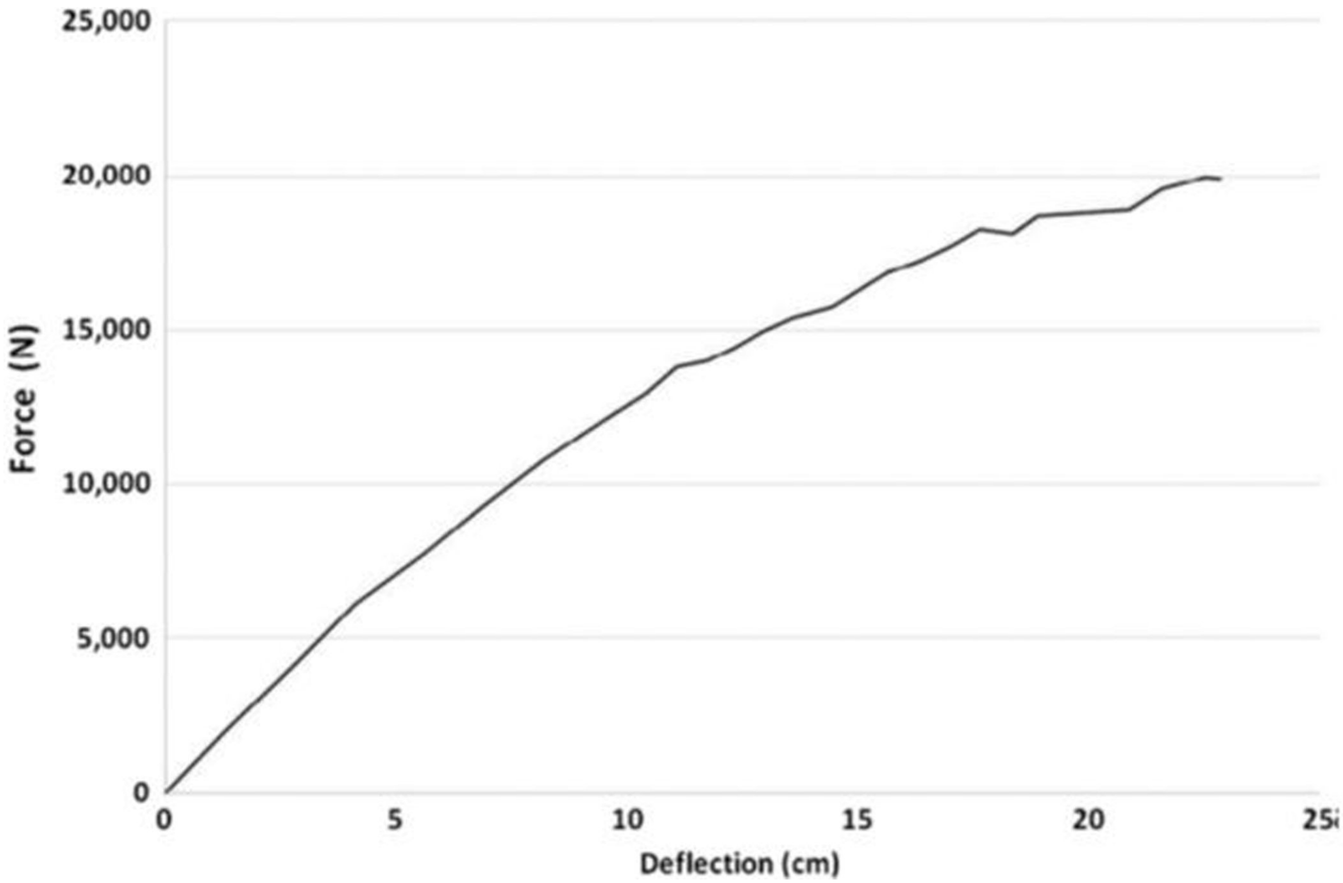

Fig. 6.
Force-deflection curve for Allis Chalmers 5040 ROPS static longitudinal test.

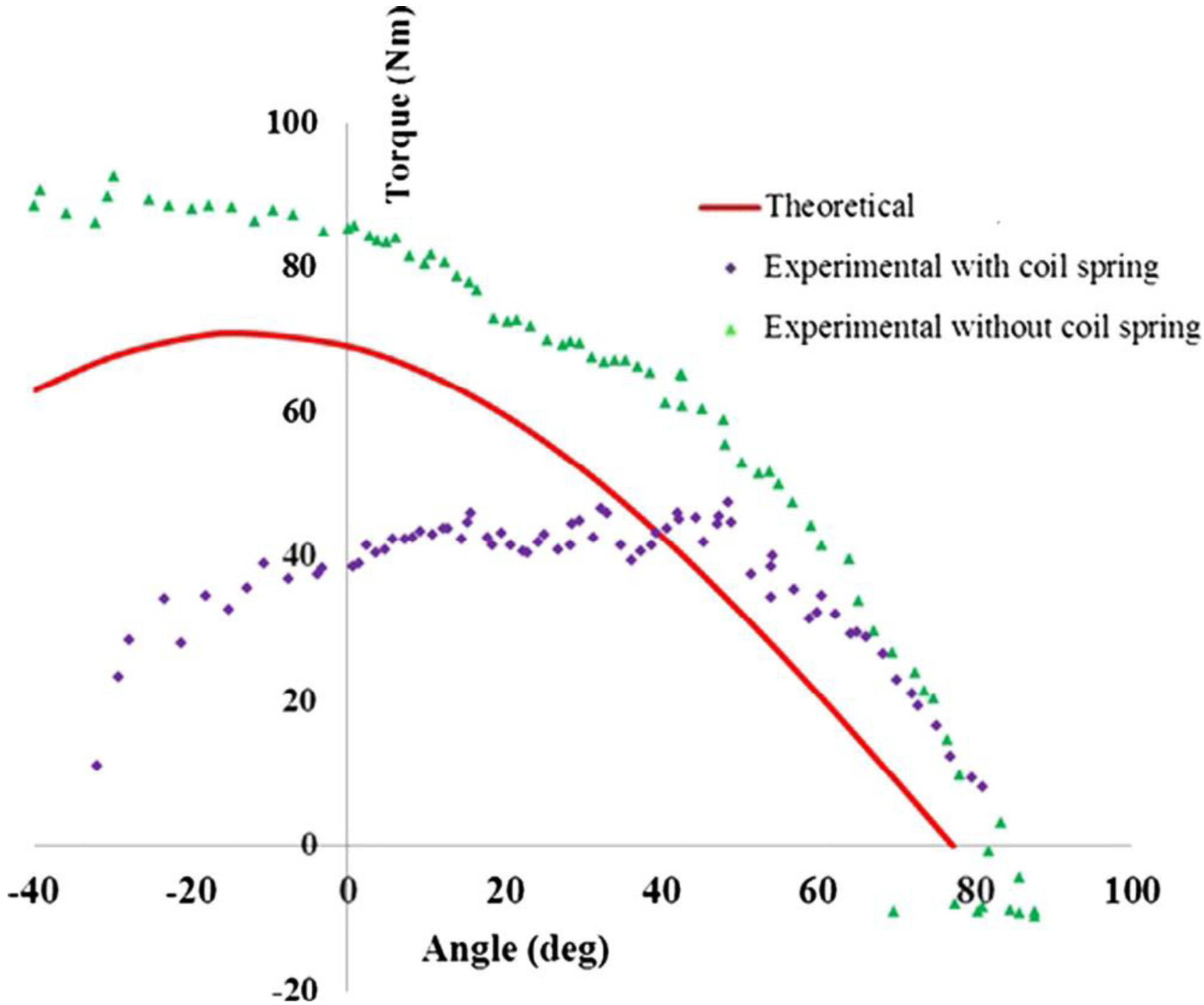

Fig. 7.

Actuation torques for raising foldable ROPS with and without coil spring assist - minus 40 and plus 90 degrees is down and up position, respectively.

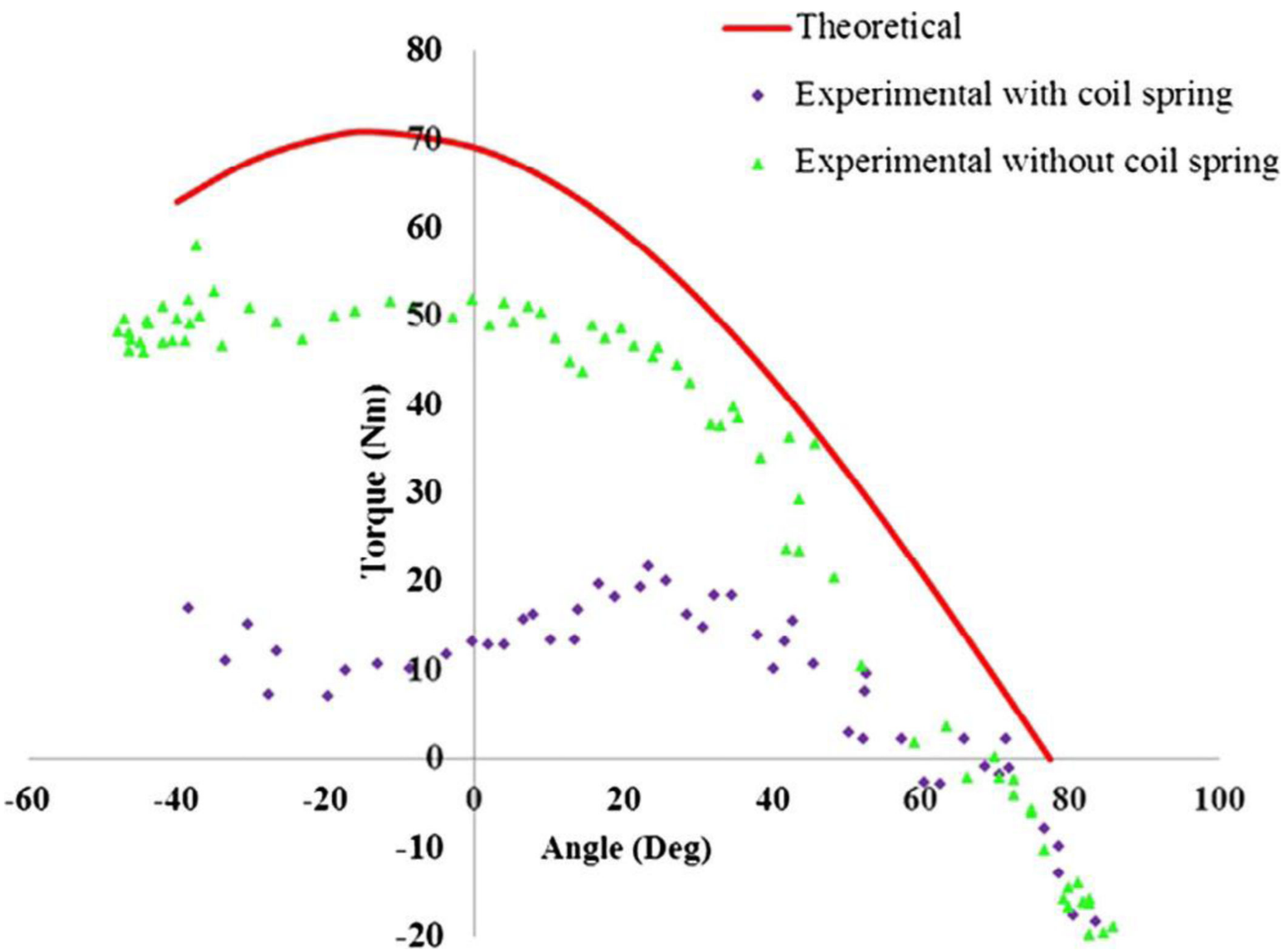

Fig. 8.
Resisting torque to lower the foldable ROPS with and without coil spring assist.

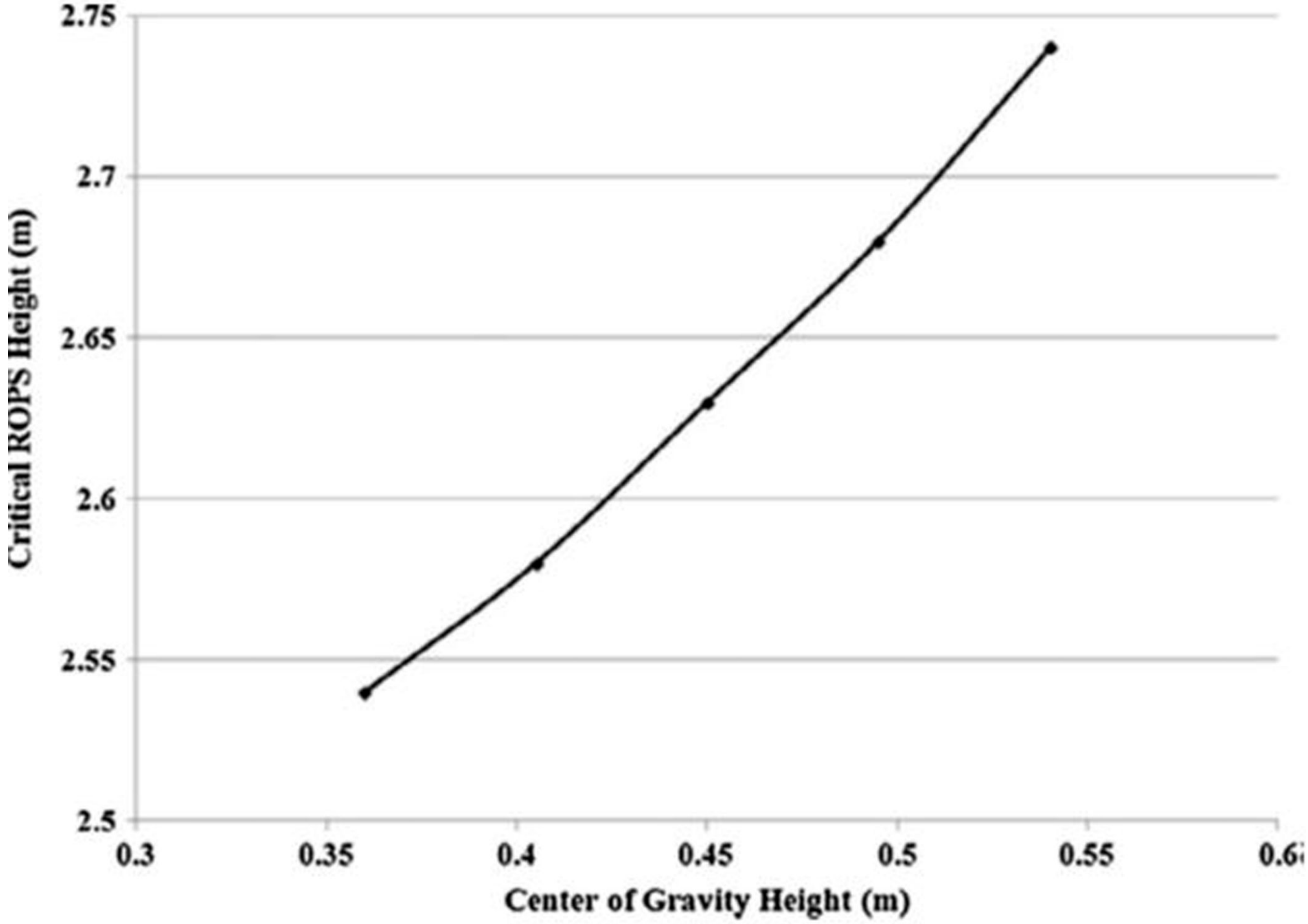

Fig. 9.
Influence of center of gravity height on critical ROPS height.