Winch Pull Force Calculation at Ross Shaft 4850L Station

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INTRODUCTION

Cryostats need to be constructed underground for the DUNE experiment at SURF. Each are constructed from a framework of large steel beams. Logistical challenges involve transporting the beams down the Ross Shaft. The longest beams, **Beam G**, will be pulled out of the Ross Shaft 4850L Station from the North Skip Compartment using a winch. The pull force needs to be calculated to specify the winch required to extract the I-beam.

Constraints

The pull force depends on the max. load capacity of the North Skip Compartment Materials Transport Cage and the dimensions of the Ross Shaft 4850L Station. If an item cannot fit in the shaft, it cannot be extracted out of the shaft:

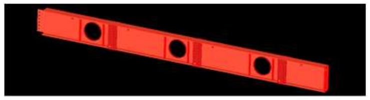

Figure 1. 3D model of Beam G

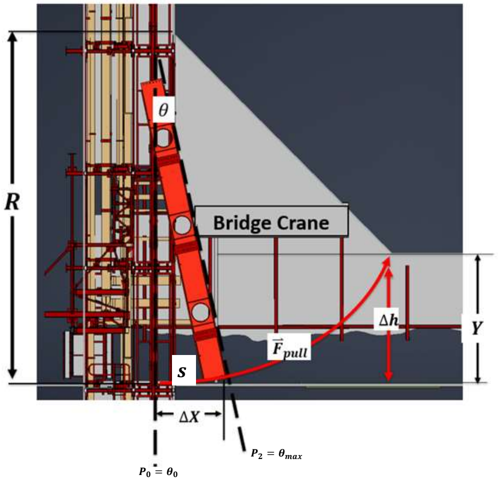

Figure 2. 3D model of Ross Shaft 4850L Station with incorporated crane and Beam G.

Additionally, the displacement out of the shaft was given at 10ft. Finally, due to the hanging position of the I-beam and the pull of the winch, there is a swinging motion of the I-beam out of the shaft—forms an arc ($s = R\theta$).

Constraints	Direction (Meters)				Degrees	
	x	y	z	r	θ	ϕ
Max. Height Under Crane Hook:	8.3	8.6	-			
Ross Shaft Materials Transportation Skip ("RFP 2022 Statement of Work 1.0 Skip Transport Cage" and "UGI H1 227						
Center of Ross Steel Set:	2.1	15.0	1.0			
North Skip Dimensions:	1.7	18.3	1.4			
Center Line of North Skip Hook Height:	0.9	14.57	2.4			
Max. Load Constraints:	1.1	13.6	0.5			
Lift load off Skip Floor:	-	0.6	-			
	LBS	TON	KG			
Max. Material Mass on Integrated Hoist inside of Skip:	18739	8.5	8500			
Max. Hoist Capacity Requirement:	25353	11.5	11500			
Tare and Payload:	37000	16.8	16783			
I-Beam Constraints ("Doc No.: ST0806378_04")						
Dimensions:	1.1	13.64	0.5			
Half Dimensions:	0.6	6.8	0.2			
	LBS	US TON	KG			
I-Beam Mass:	16535	8.3	7500			
Calculations						
From CL of Skip Rope to Drift Ceiling:	10.9	14.6	1.4			
Rope hoist in Skip Length:	-	0.9	-			
Load inside of Skip:	1.1	13.96	1.4			
Bottom of I-Beam						
Distance of edge of beam to Ross Brow_Bottom of Beam:	10.3	14.6	1.0	17.9	54.6	35.4
Load inside Skip to 10ft out into Brow_Bottom of Beam:	3.0	14.0	1.0	14.3	77.7	12.3
Winch Blocks on Drift Ceiling in relation to I-Beam:	15.1	4.5	-	15.7	16.5	73.5
Bottom Edge of Beam to Winch Rope Block Distance:	13.3	4.6	-	14.1	18.9	71.1
Bottom Edge of Beam to Drift Ceiling Height_Load Block1:	15.1	4.0	1.0	15.6	14.9	75.1

Table 1. Constraints used in calculation of winch pull force

Methods

1. Basic kinematics using the constraints, and input from engineering personnel about time to extract I-beam 10ft out of the shaft to figure out the following:

10 ft out into Ross Brow		I-Beam Motion	
Measures	Symbols	X-Direction	Y-Direction
Displacement[1]	Δ in meters (m)	3.05	13.96
Time[2]	Δt in seconds (s)	60	60
Average Velocity[2]	ΔV in meters per second (m/s)	5.08E-02	2.33E-01
Average Acceleration[2]	a in meters per second-squared (m/s^2)	8.47E-04	3.88E-03

[1] **Note:** The following are assumptions based on design specifications.
[2] **Note:** The following are based on assumptions. The rates will in fact vary.

Table 2. Basic kinematics for motion of I-beam 10ft out of Ross Shaft .

2. The pull force was derived from the x-component, $\sum F_x = F_{pull} - T sin\theta = ma_x = 0\ (N)$, and the y-component, $\sum F_Y = T cos\theta - w = ma_Y = 0\ (N)$, of the sum of forces involved. Set T equal to each other to solve for the pull force as follows:

$$\frac{F}{sin\theta} = \frac{w}{cos\theta} \therefore F_{pull} = w\frac{sin\theta}{cos\theta} = w\, tan\theta$$

3. Using concepts from Conservation of Energy, the **work-energy theorem for motion along a curve** for initial position to final position of the **bottom of the I-beam 10ft out of the shaft is**[1]:

$$W = F_{\parallel}s = (F\, cos\theta)s = \int_{P_1}^{P_2} F\, cos\theta\, dl$$

$$= \int_{\theta_0}^{\theta} (w\, tan\theta)\, cos\theta\, (Rd\theta) = wR(1 - cos\theta)$$

Results

The static and dynamic mathematical results for the pull force 10ft out of the shaft are as follows:

Pull Force 10ft Displacement into Ross Brow			
Measures	Variable	Value	UNIT
x-displacement:	ΔX	3.05	m
Max. Load Height:	R	14.0	m
Max. Angle:	θ	12.3	degrees
Mass:	m	11500	kg
		25353	lbs
Acceleration Constant:	a	9.81	m/s^2
Weight:	w	112815	Newtons
	w	25362	ft-lbs
Pull force on I-Beam:	F_{pull}	24625	Newtons
	F_{pull}	5536	ft-lbs
	ΣT	25959	ft-lbs
	T_X	-5536	ft-lbs
	T_Y	25362	ft-lbs
	$T_{\perp} = T \bullet dl$	0	ft-lbs
Work of Winch Rope:	*W*	36239	Joules
Max. Change in Height:	Δh	0.32	m
	Δh	1.05	ft
Time:	Δt	60	sec
Average Power:	$P=F_{\parallel}v$	1840.95	Watts
	$P=F_{\parallel}v$	1.84	kWatts
	$P=F_{\parallel}v$	2.47	hp

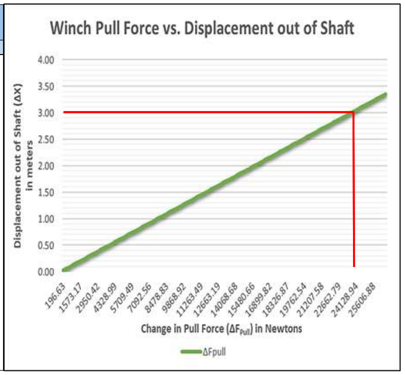

Figure 3. Table for the static calculation for pull force and a graph of the dynamic calculation of the pull force 10ft out of the shaft.

Conclusion

The pull force of 24625 Newtons (5536 ft-lbs) with a power of 1.84 kWatts (2.47hp) using the max. load capacity 11500kg (25353 lbs) of the North Skip Cage is sufficient to pull the I-beam out 3m (10ft) given its mass is 7500kg. The selection of winch ought to match the power required to pull the I-beam out of the shaft.

Acknowledgement

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References:

1. Young, Hugh D., & Freedman, Roger A. (2020). *University Physics with Modern Physics, 15th Edition*. Pearson Education, Inc., pgs. 185-186.